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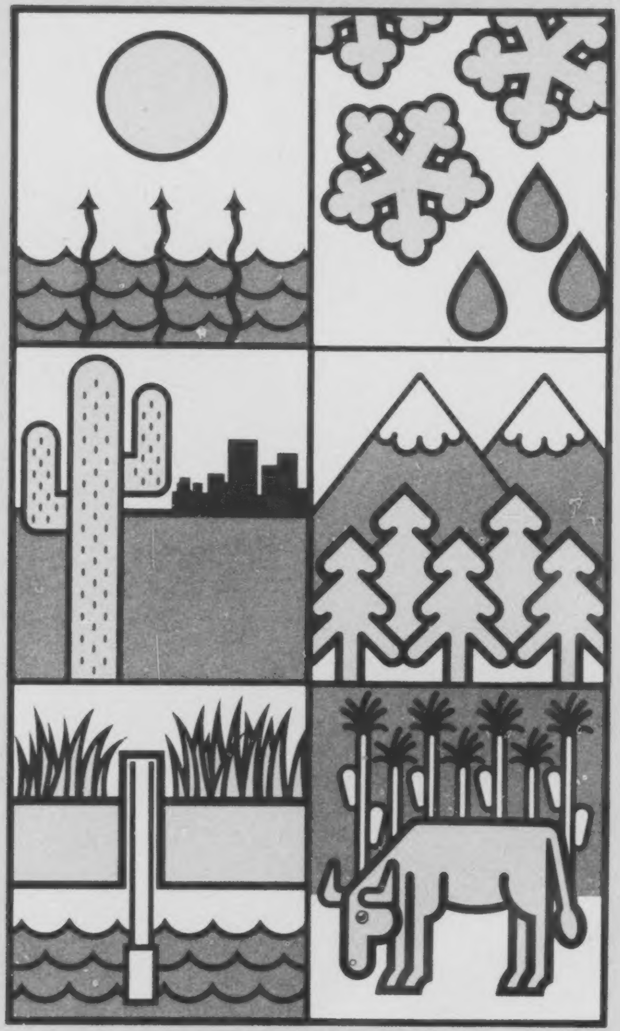
Water-Related Technologies

for Sustainable Agriculture in U.S. Arid/Semiarid Lands



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Water-Related Technologies

for Sustainable Agriculture in U.S. Arid/Semiarid Lands

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Foreword

Water is a major limiting factor in most areas where Western arid and semiarid agriculture is currently practiced. Increasing water demands from nonagricultural users plus growing problems of ground water depletion, salt buildup in agricultural soils, and water-quality deterioration are causing heightened concern about the sustainability of Western agriculture. A major part of this concern is focused on whether the Federal agricultural system is prepared to meet the changing needs of Western agriculture and whether technology can assist in providing the Nation with Western agricultural production that is sustainable and profitable over the long term.

This report assesses existing and emerging water-related technologies for their ability to support long-term productivity of arid/semiarid agricultural plants and animals in the context of institutional factors, water supply/use relationships, and the characteristics of the renewable natural resource base on which agriculture depends. The study was requested by the House Committee on Agriculture and endorsed by the Senate Committee on Environment and Public Works, Subcommittee on Water Resources. The technologies examined by the study are generally directed toward: 1) improving efficiency of water use, whether for rain-fed (dryland and rangeland) systems or irrigation; 2) improving water management, storage, and distribution for agriculture; and 3) augmenting existing supplies with additional water not previously available. The report also identifies a number of options for congressional action. A background paper containing examples of application of arid/semiarid agricultural technologies in foreign countries has been published separately as part of this assessment.

The Office of Technology Assessment (OTA) greatly appreciates the contributions of the advisory panel, working groups and workshop participants assembled for this study, the authors of the technical papers, and the many other advisors and reviewers who assisted us, including farmers, ranchers, agricultural scientists in government and universities, and experts in the private sector. Their guidance and comments helped develop a comprehensive report. As with all OTA studies, however, the content of the report is the sole responsibility of OTA.

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Summary and Findings

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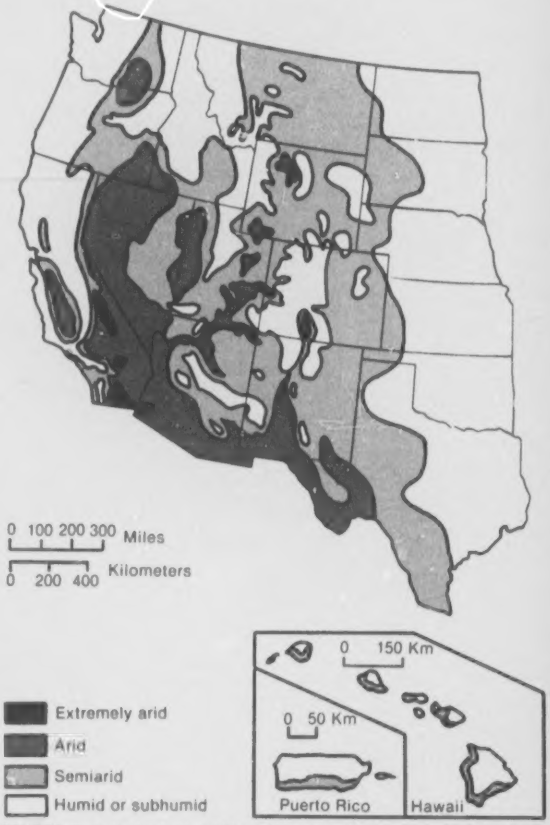
Chapter I

Summary and Findings

INTRODUCTION

As a Nation with bountiful resources, the United States has rarely faced natural resource limits. In the short history of this country, there have always been more lands and more resources to develop and a philosophy that technology could supplement natural resources when needed. Increasingly, however, some Western States are experiencing resource limitations related to water use and distribution that challenge the full capacity of existing social and technical institutions. The water problems to face this region and, therefore, the Nation in the 1980's and 1990's are likely to expand and intensify for agriculture. Stretching resources to accommodate the West's continuing growth while protecting existing patterns of water demand may require levels of technical input no longer economically feasible. Concerted Federal, State, and local action will be needed to help build a sustainable Western agriculture that is profitable for the Western farmer and rancher and that effectively addresses the complex and interrelated problems surrounding the agricultural use of Western water. A strong Federal role will remain fundamental to help bring about necessary changes.

Figure 1.—Arid and Semiarid Regions of the United States



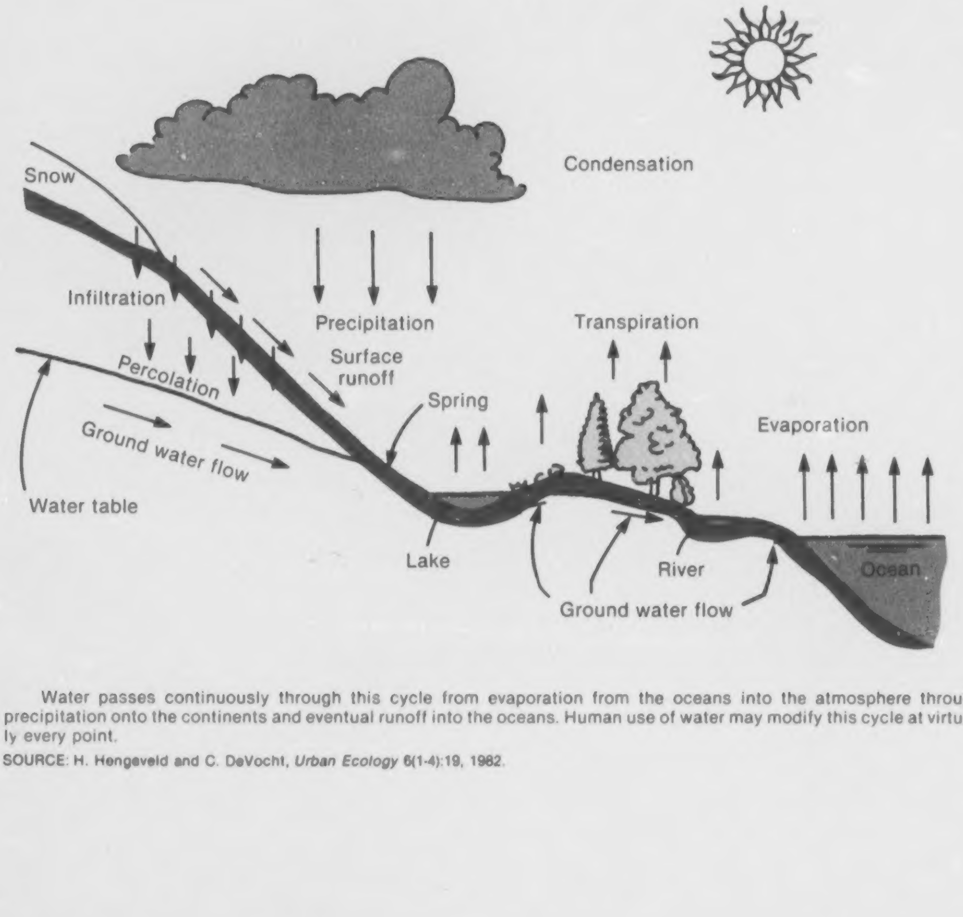
SOURCE: Carle Hodge (ed.), *Aridity and Man* (Washington, D.C.: American Association for the Advancement of Science, publication No. 74, 1963).

This study assesses the role of present and emerging water-use technologies for sustaining the long-term agricultural productivity of arid/semiarid agricultural plants and animals and the renewable natural resource base on which agriculture depends. The study considers increased demands on the resource, concerns about water quality, and the capacity of existing institutions to respond effectively and equitably to growing demands. Congressional interest in this topic is important because the arid/semiarid West (fig. 1) makes significant contributions to this country's agricultural production, providing unique benefits not easily replaced by the other regions of the United States. Its large expanses of land nurture cereal grains and livestock. Its dry and disease-free environment is especially suited to seed production and certain kinds of agricultural research. When irrigated, its soil, aided by low humidity and many cloud-free days, produces high-value specialty crops such as fruits, nuts, and table vegetables. Much of the research and development (R&D) of agricultural technology that now benefits the entire United States originated in the West, where water application could be carefully controlled.

This report is organized into two parts: background chapters on the state of the renewable resource base and associated water institutions (chs. II-V) and technology chapters containing assessments of near- and long-term technology potentials (chs. VI-XI). Technologies are organized in particular chapters according to the principal components of the hydrologic cycle (fig. 2) the technologies are meant to manipulate. Because water is a key factor dictating the types of agriculture that can be sustained in the water-short West, knowing the impacts of a particular water-related technology throughout the water system is critical. Benefits to one user upstream could mean losses to another user downstream in reduced flow, reduced quality, or altered timing of flow. Alterations in surface water at one site could affect ground water supplies at another hydrologically interconnected site. Moreover, technologies and land uses may overlap at particular sites.

As used in this report, the term "renewable natural resource base" includes soil, water, and all the physical, chemical, and biological components of agricultural resource systems. "Long-term," as used in this report, means more than one human lifespan (approximately 70 years) from the date of this report.

Figure 2.—The Hydrologic Cycle



Water passes continuously through this cycle from evaporation from the oceans into the atmosphere through precipitation onto the continents and eventual runoff into the oceans. Human use of water may modify this cycle at virtually every point.

SOURCE: H. Hengeveld and C. DeVocht, *Urban Ecology* 6(1-4):19, 1982.

MAJOR FINDINGS

The following three major findings of this assessment are the synthesis of individual chapter findings which are discussed in more detail below:

- If agriculture in the Western United States is to be conducted in a sustainable fashion, a systems approach to decisionmaking regarding policies, plans, and programs affecting the agricultural resource base and water-related technologies is a fundamental need, one that generally is lacking throughout government.
- The goal of sustaining long-term productivity of the agricultural resource base in the Western States is not being advanced effectively by some existing Federal activities.
- To ensure sustainable Western agriculture, users must be involved in and must perceive equity and fairness in decisionmaking about water-related technologies and resolution of conflicts over water use. Improved mechanisms are needed to expand this involvement.

Western Agricultural Production

Products of Western agriculture constitute a large share of the total income derived from farming and ranching in the United States. In 1980, cash receipts from marketing crops and livestock and their products in the Western States accounted for approximately $59.3 billion, or about 43 percent of the income derived from farming in the United States. Some 30 percent of this sum came from export markets.

Unlike the Eastern United States, much of the land in the West is federally owned:

	Federal	*Non-Federal*	*Percent Federal*
	(in millions of acres)		
17 Western States....	368	790	32
31 Eastern States	34	705	5

The amount of public land varies from State to State, from some 85 percent of Nevada to about 1 percent of Kansas and Nebraska. These public lands are used largely for livestock grazing and include major water-producing areas. The Federal ownership of these lands has generated Federal policies on use and management, policies that can substantially affect the sustainability of Western agriculture.

Of the three types of agricultural production (see box A) used in arid/semiarid regions, rangeland and dryland agriculture are the most extensive in area and rely on precipitation for water supplies. **Rain-fed agriculture makes important contributions to the economy and lifestyle of the West and is likely to increase in importance.** Present-day irrigation agriculture is especially significant because of the large amounts of energy and supplemental water involved. It allows crop production in areas where it might otherwise be impossible, and farmers who irrigate generally have higher and more stable yields and can risk growing crops of higher value. However, irrigation agriculture is the subject of particular controversy and concern at present. Some crops that are irrigated are surplus. Moreover, competition for these water resources is increasing from industries and municipal users who can afford to pay more for their water. Finally, depletion of ground water resources threatens agricultural producers and rural communities and diminishes the possibility of using this resource in the future. These factors lead many analysts

Box A

Three broad types of agricultural production are common in arid/semiarid regions:

- Rangeland agriculture—usually involves grazing domestic livestock on grasses, grasslike plants, forbs, and shrubs on lands traditionally considered unsuitable for cultivation.
- Dryland farming—involves crop production through cultivation of the land and relies on precipitation to supply plant-water needs.
- Irrigation agriculture—involves crop production through land cultivation and uses additional water to supplement normal precipitation.

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to believe that **in the future Western irrigation agriculture as practiced today will diminish in productivity and profitability in some areas.**

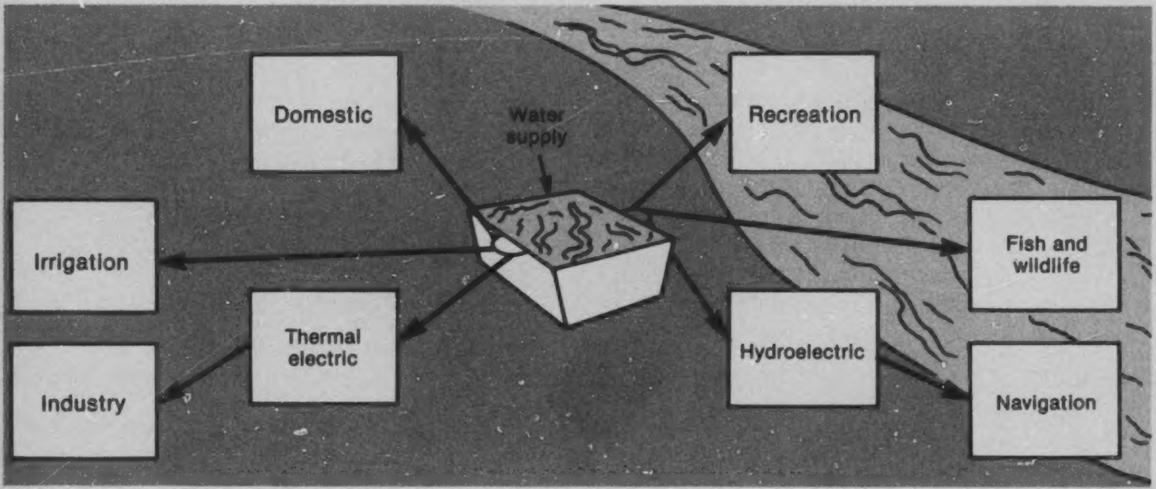
Water Supply and Use

Available estimates of water supply and use indicate that **almost half of the Western United States is experiencing water-supply problems in relation to demand.** Surface water shortages exist annually or seasonally in at least some portion of each of the major water resources regions of the Western States. In almost all cases, these shortages are offset by water reuse and ground water pumping. In much of the Southwest and southern High Plains, ground water is being withdrawn faster than it is replaced (often called ground water "mining") in order to sustain developed levels of use. Where water supply is not being consumed, competing nonconsumptive uses, such as instream flow requirements for hydroelectric generation, waste assimilation, recreation, and habitat maintenance, increasingly create scheduling conflicts for offstream uses (fig. 3). **Present trends and experience indicate that every additional drop of water conserved, and thus available, enables more growth and development, raising demand levels further. Effective water-use management will necessitate attention to demand as well as supply aspects of water use.**

The availability of water for agricultural use varies by location and over time. Water supply depends on variations in components of the hydrologic cycle—precipitation, evaporation, transpiration, infiltration, and runoff. Because these components interrelate, a change produced by technology in one component of the cycle will inevitably affect other components.

The potential for a given technology to produce additional water or to conserve existing supplies is difficult to evaluate and will remain so unless the quantities of water involved in the hydrologic cycle can be defined more accurately. Various responsibilities for

Figure 3.—Conflicts in Instream v. Offstream Use



SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000*, vol. 2, part III (Washington, D.C.: U.S. Government Printing Office, 1978), p. 129.

the collection, synthesis, and dissemination of hydrologic information are delegated among a number of Federal and State agencies (table 1), resulting in a variety of data bases and data interpretations that are often not compatible. **Important gaps in data exist, and few regional syntheses of data have been made.** Short-term climatic fluctuations affecting water supply can be accommodated in management and planning processes through statistical analysis of past trends; there is no reliable method for predicting long-term fluctuations.

The most important source of renewable surface water supplies in the Western United States is the mountain snowpack. When the snowpack melts in the spring and summer, it supplies an estimated 70 to 100 percent (depending on location) of the total annual surface runoff for all river basins except the Texas-Gulf region. Relatively little research attention has been given to the snowpack. Technologies such as weather modification and the forecasting of streamflow to improve reservoir management would benefit considerably from increased understanding of the snowpack's dominant role in renewing surface water supplies.

Water Quality

Water quality is determined both by the nature of a pollutant and by the concentration of that pollutant in water. The kinds and amounts of impurities in water depend on a number of environmental factors, such as the source of the water, the physiographic characteristics through which the water moves, and the effects of human activity on water. The types of water pollution can be categorized as follows:

1. municipal sewage and other oxygen-demanding wastes,
2. infectious agents,
3. synthetic organic chemicals,
4. mineral substances and inorganic chemicals,
5. sediments,
6. plant nutrients,
7. radioactive substances, and
8. heat.

Since the volume of water in the Western United States is lower than that in the more water-abundant Eastern part of the country, any given water use in the West has a greater

Table 1.—Federal Water-Data Collection Agencies[a]

	Government agencies						Independent agencies			
In-house data programs	USDA	DOC	DOD	DOE	DOI	DOT	EPA	IBWC	NRC	TVA
Surface water	X	X	X	X	X	X	X	X	—	X
Ground water	X	—	X	X	X	X	X	X	—	X
Water quality	X	X	X	X	X	X	X	X	—	X
Water use	X	X	X	X	X	—	—	—	—	—
Environmental impact	X	—	X	X	X	X	X	—	—	X
Ecology	X	—	X	X	X	X	X	—	—	X
Management effects	X	—	X	X	X	X	X	—	—	X
Basin studies	X	—	—	—	X	X	X	—	—	X
Real-time sensing	X	X	X	—	—	X	X	—	—	X
Remote sensing	X	X	X	—	—	X	X	—	—	X
Data sensing	X	—	X	X	X	—	X	—	—	X
Instream use	X	—	—	—	X	—	—	—	—	—
Water rights	X	—	—	—	X	—	—	—	—	—
Floods	—	X	—	—	X	X	—	—	—	X
Energy	—	—	—	X	X	—	X	—	X	—
Nuclear	—	—	—	X	X	—	X	—	X	—
Precipitation quality	—	—	—	—	X	—	X	—	—	X

KEY: USDA—U.S. Department of Agriculture; DOC—Department of Commerce; DOD—Department of Defense; DOE—Department of Energy; DOI—Department of the Interior; DOT—Department of Transportation; Independent agencies: EPA—Environmental Protection Agency; IBWC—International Boundary & Water Commission; NRC—Nuclear Regulatory Commission; TVA—Tennessee Valley Authority.

[a] For the 1981-82 fiscal year, 26 Federal agencies, representing six departments and four independent agencies, collected water resource data.

SOURCE: U.S. Department of the Interior, Geological Survey, Office of Water Data Collection, *Plans for Water Data Acquisition by Federal Agencies Through Fiscal Year 1983* (Reston, Va.: 1982), p. 7.

potential for causing water-quality degradation. The limited supply of Western water requires that each unit of water be more fully used, resulting in patterns of reuse in which each unit of water is used consecutively as it moves downstream. Thus, water may be removed from a river and partially consumed for irrigation; the return flow may be stored in a reservoir and subsequently reused to generate hydroelectric energy; and the remainder may be withdrawn by a municipality for human consumption. The return flows from each of these uses often have increasing levels of pollution that, left untreated, can threaten uses downstream, including agricultural uses.

Most water-quality problems appear to be site-specific. The data base describing the quality of water in the Western United States is incomplete, however, and few integrated analyses of water contamination as it affects water reuse, environmental characteristics, or public health have been performed.

The term "water quality" in agriculture refers primarily to the quality of water used for farm and ranch water supply, livestock watering, and irrigation. In evaluating the relationship between water quality and agriculture, two aspects must be considered:

1. the effect of agricultural uses on the quality of water for other uses, and
2. the effect of water quality on various agricultural uses.

The highest quality water required in agriculture is for domestic farm and ranch consumption. Much of the water used in this way is well water, which in many areas is not routinely monitored for quality nor subjected to any routine treatment prior to use. The quality of this water source is particularly susceptible to degradation because of the many potential sources of contamination in the farm and ranch environments.

The quality of water used in irrigation is also very important. When water applied in irrigation is lost to evapotranspiration during plant growth, salts contained in that water are left behind in the soil. **Continued reuse of streamflows for irrigation without prior treatment has become a necessity in many of the water-short areas of the Western United States. This reuse can result in the gradual buildup of salts and agricultural chemicals in the soil and in water that is ultimately detrimental to long-term agricultural productivity.**

Agricultural water pollution can be reduced by using improved management practices and methods that result in fewer contaminants being released into the water supply. However, present monitoring and control measures may not be sufficient to prevent deterioration of water quality caused by Western water use for either agricultural or nonagricultural activities—e.g., municipal and industrial activities.

Institutions Affecting Western Agricultural Water Use

Distribution of water in the Western United States among uses and users responds to two major institutional forces—the legal system and the market system. The legal system defines rights and responsibilities regarding the use of water; the market system allows water to be bought and sold, and thus transferred between uses and users. **The Western agricultural water user is, at best, moderately uncertain about water use and the adoption of technology affecting water use because it is unclear how legal and economic institutions might change as demands for water increase.**

The Western State water institutions developed in response to the surrounding conditions of aridity and the initial character of Federal ownership of the water and land. Their focus was on allocating water-use rights to individuals as property rights. States deferred to Federal agencies for large-scale water-resources planning and development because of the Federal Government's financial and technical capabilities and its broad geographic jurisdiction that facilitated interstate river basin development.

At the time Western law doctrines (Federal, State, and interstate) were developed, the level of definition given to water rights and duties was adequate to address early development needs. Water law divided the resource into water-supply categories, the major categories at the State level being surface water and ground water. In recent years, water-quality programs have been developed with distinct bureaucracies and regulatory responsibilities separate from those programs related to water supplies. This treatment of water has caused conflicts and confusion among users within and between States and has made water planning and management problems more severe. **As water-use demands increase and values change, more precise definition of such concepts of beneficial use will be required to allow the user greater assurance of return on investments in water "saved."**

Growing demands are creating conflicts among agricultural, energy, industrial, municipal, Federal reserved water-right holders, environmental, and other uses and values and suggest that water in the West will become more expensive. Until now, Federal sponsorship of many development activities provided water at well below its "cost" or "value" relative to much non-Federal water. This sponsorship has slowed the development of Western water markets and has shaped the character and patterns of agricultural water use in the Western United States. However, as demands for water for nearly all purposes increase and as the scarcity of water is recognized, pressures will mount to shift water to new uses and users. The rules of economic efficiency will support arguments that the development of water markets may be desirable. Making such changes, however, must be viewed in a context broader than the primary or first use of the water. Whether the water is used for irrigation, navigation, recreation, or hydropower as the primary use, that water also generates secondary and tertiary incomes to local economics. **Transferring substantial amounts of water to a new use will have a profound effect on the people and on the supporting resources that are left behind.**

In the past two decades, States have begun to take a more active role in resolving these growing conflicts of water use and the associated social effects of the choices being made. However, **direct Federal involvement to address Federal water issues, topics of broad geographical jurisdiction, international impacts, and equity concerns and to support and assist States' efforts will be necessary to ensure the sustainability of Western agriculture.**

Technologies: Making Optimal Use of the Hydrologic Cycle for Arid/Semiarid Agriculture

Evidence suggests that some new and emerging technologies have potential for sustaining the long-term productivity of Western agriculture. These technologies are wide-ranging, and their effective application requires an understanding of their interrelated impacts on the agricultural resource base. Such technologies involve several natural and social science disciplines, including hydrology (understanding water-related impacts), plant and animal science (adapting plants and animals to resist environmental stress), engineering (improved irrigation-system management), agronomy (cultivation practices and planting techniques), and interdisciplinary sciences for integrated agricultural land and water management (multiple-use of rangeland and cropland, flexible cropping).

Water-related technologies for arid/semiarid agriculture are generally directed toward:

1. improving efficiency of use (and thus minimizing "waste" in such practices as irrigation),
2. augmenting existing supplies with additional water not previously available for agricultural purposes,
3. preserving water quality, and
4. improving supply and distribution.

Technologies Affecting Precipitation and Runoff

The renewable water resources of the West originate as precipitation from air masses moving across the region. Surface runoff represents that fraction of this precipitation not consumed by evapotranspiration or infiltrated into the soil and ground water. Three major classes of technology have evolved around modifying or anticipating the surface runoff fraction of the original precipitation: weather modification, watershed management, and water-supply forecasting. Each of these technologies has some potential on at least a local, site-specific basis. Evidence does not yet exist, however, to demonstrate that these are generally accepted operational technologies for sustainable agriculture.

Evaluation of any technology designed to modify or forecast precipitation and/or runoff from hydrologic environments in the region would benefit from a more integrated approach to the study of the hydrologic regimes of the Western United States than that which now exists. Moreover, hydrologic research activities and priorities should reflect the fact that most of the annual surface runoff and ground water recharge in the West comes from the mountain snowpack.

WEATHER MODIFICATION

Weather-modification technologies are designed to increase the amount of precipitation over that which occurs naturally. This is done by injecting artificial nucleating agents, such as silver iodide, into suitable air masses. The two weather-modification technologies that have received the most attention are those involving: 1) winter storms that cross the major mountain ranges of the Western United States, producing the snowpack of the mountain watersheds; and 2) the summer cumulus clouds that produce both rain and hail, often in large amounts over limited areas. Of the two, precipitation augmentation from winter storm systems by "cloud seeding" appears to show the most promise. **This technology has been developed within a solid scientific framework creating a body of knowledge that should facilitate future advances.**

WATERSHED MANAGEMENT

Two major classes of watersheds occur in the Western United States: 1) highland watersheds, located in the major mountain ranges and consisting of the untimbered "alpine" zone (above the timberline) and the timbered "montane" zone; and 2) lowland watersheds consisting of grass- or brush-covered valleys and plains. Watershed-management technologies are designed to increase surface runoff by vegetation removal or replacement or by other surface modifications.

No proven technologies exist to increase water yield from the alpine zone. This area may be the most efficient and productive source of water in the Western United States, and a passive, conservative management approach may be the most beneficial and effective management technology at present for downstream users.

In certain situations in the montane zone, vegetation management through timber harvesting may produce local increases in water yield. It may be difficult, however, to detect increased yields at points downstream where arid/semiarid agriculture is practiced because such increases, when combined with the entire volume of watershed runoff may not be discernible using existing stream-gage technologies. Moreover, the ability to predict results of application on an unstudied watershed is difficult because of the range of hydrologic environments in the mountains of the West relative to that represented by existing experimental results. At some sites the effects of timber harvest on soil erosion, other components of the hydrologic cycle, or existing wilderness values may negate potential beneficial effects for downstream arid/semiarid agriculture.

Results of attempts to produce additional surface runoff from lowland watersheds have been varied because of the natural hydrologic variability of the lowland watersheds and the range of purpose of the technologies. Because practices are very site-specific, they have more local than regional significance. In most cases where the dominant vegetation consists of shrubs and grasses, management should emphasize forage production and erosion prevention rather than surface runoff production. Where surface runoff is collected and used for cultivated crops and animal watering (runoff agriculture), water-management practices can provide an important local water supply.

STREAMFLOW FORECASTING

Water-supply forecasting is one of the most important technologies related to precipitation and runoff in the Western United States for long-term sustainable agriculture. Improvements in the accuracy of these technologies will entail advances in understanding the impacts of weather modification and watershed management on the hydrologic environment. **Improved water-supply forecasting could provide the link between the resource and the water user or planner because it directly relates to the timing and volume of water available to downstream or lowland agriculture.**

A wide range of forecast models exists, from very sophisticated computer simulation technology to simpler statistical correlation models. Research has indicated that no single forecast model may be sufficient for all the hydrometeorological environments in the West. Research also suggests that progress in accurately forecasting streamflow for certain regions in the Western United States would reap considerable economic benefits for agriculture.

Technologies Affecting Surface Water Storage and Delivery

Natural streamflow and precipitation seldom meet agricultural demands for water in the Western States. Three approaches make more surface water available when demand exceeds supply:

1. increasing the total amount of water in storage,
2. augmenting supplies with additional water, and
3. stretching existing water supplies by conservation.

Currently, opportunities to develop large sources of previously unavailable surface water or to augment existing supplies are feasible technologically but are limited by economic, environmental, legal, and social considerations. They are unlikely to add significant amounts of water to irrigation supplies in the future. Technologies that reduce water losses (i.e., conserve water) in storage and delivery systems can be applied relatively easily but tend to be expensive. In addition, their effects on the entire hydrologic cycle are often difficult to measure and their application, at times, can have unexpected, negative effects on riparian (areas of shrubs, trees, and grasses generally along streambanks) and wetland wildlife habitats.

TECHNOLOGIES THAT STORE AND AUGMENT WATER SUPPLIES

Technologies that increase the amount of water in storage include storage facilities, desalination processes, and interbasin transfers of water.

Storage Facilities.—The extensive and complex system of large and small reservoirs in the Western States represents about 79 percent of storage capacity in the Nation. These storage areas include a few reservoirs that contribute much to the total storage capacity, a sizable number of medium-sized reservoirs, and an even larger number of farm and ranch ponds. Storage facilities permit more convenient and efficient use of available water supplies by downstream agricultural users. Construction technologies for reservoirs are well developed, and technologies to manage reservoirs are advancing rapidly.

The Federal Government has a sizable investment (at least $26 billion) in completed water resource projects and owns some 2,000 dams, ranging in size from small reservoirs to large, multipurpose projects. While the benefits to irrigators and other users have been sizable, the costs have also been substantial.

Barriers to new, large-scale developments are not technological; they are physical, economic, and environmental. **Because of these constraints, many experts expect that the Federal role in building and operating new, large-scale water-storage facilities will diminish markedly in the future.** New storage facilities are likely to be smaller, and their construction may depend increasingly on private and non-Federal public investment. Innovative cost-sharing arrangements could be encouraged between private and public developers and among local, State, and Federal governments.

Desalination.—Desalination (removal of dissolved salts from brackish water, seawater, or salt-degraded water) is a technology that can supplement freshwater supplies. Desalination can be accomplished by many methods and has proven to be reliable for small amounts of water. **High costs are the major current limitation to use of desalination; further development is needed before the process can produce low-cost freshwater.** Brine disposal is also a problem. These considerations now limit production of desalted water to municipalities and industries and exclude most agricultural uses.

Interbasin Transfers.—In the Western United States, regional transfers of water from one river basin to another—e.g., the Colorado-Big Thompson project—have been in operation for many years. Current attention focuses on proposals to transfer water from areas of supposed surplus (e.g., Alaska and the Missouri River) to Western stream systems for irrigation use. Such **transfers will present considerable problems for the foreseeable future.** First, the cost of irrigation water from an interbasin transfer would probably be prohibitively expensive. Second, such transfers will present complicated environmental, political, legal, and institutional problems. **Most important, however, surplus water may not be available for transfer since many areas are realizing the present and future values of their water onsite.**

TECHNOLOGIES THAT CONSERVE EXISTING WATER SUPPLIES

Technologies that conserve existing water supplies have promise for meeting short-term needs for irrigation water. These practices include flexible delivery systems for irrigation water, seepage and evaporation control, and vegetation management.

Flexible Delivery Systems for Irrigation Water.—Timely delivery of surface water to irrigation users is a crucial element of effective water management. In most arid/semiarid regions, delivery systems are based on supply rather than demand because the water supply is limited. Delivery schedules are prepared in advance and are fixed for a preset time and length. Adjustment in timing, duration, or quantity of water application is limited. This system favors water distribution over crop needs.

A variety of technologies for improving water delivery flexibility is being examined. **While the agronomic benefits of new water-delivery technologies are likely to be substantial, existing irrigation facilities and practices may require extensive modifications before these benefits can be realized.**

Seepage Control.—Seepage occurs through the sides and bottoms of reservoirs and canals. Its extent depends largely on geology, soils, and topography. Water "losses" caused by seepage can be large enough in some areas to prevent reservoirs from filling; however, estimates of the problem's magnitude are difficult to make and vary widely.

Seepage control can "save" water on a local basis, and its effects can vary widely in different locations. For example, water lost through seepage is not lost to the hydrologic cycle and is generally available for downstream users, for ground water recharge, and for plants and animals in wetlands and streams.

Although technologies to reduce seepage are available (e.g., soil sealants and methods that compact the earth), control is costly, a primary limitation to use. As the relationship between wildlife populations and standing water from inefficient irrigation is explored more fully, other limitations to use may be identified.

Evaporation Control.—In arid/semiarid lands, evaporation is high. In some regions, reservoir evaporation may reach about 40 percent of usable storage. In small reservoirs, stock tanks, and farm ponds, more water may be lost than is used productively. Since conserving collected water is one of the most economical methods of maintaining an adequate water supply, considerable research has been devoted to developing effective evaporation-control technologies. These technologies increase water supplies, in effect, by increasing reservoir capacity without new construction. They alter the processes that contribute to evaporation by:

- lessening the amount of energy that reaches the water surface to drive evaporation, and
- altering the ease with which vaporized water moves into the air.

Four methods of controlling evaporation have received attention: 1) surface area reduction, 2) reflective coatings, 3) surface films, and 4) mechanical covers. **Results from use of evaporation-control technologies have been variable and often disappointing.** Reflective coatings and surface film are unstable and ineffective if the water surface is not still. Small reservoirs arranged in clusters and of varying depths (frequently called "compartmented") experience substantially reduced evaporation when volumes are managed to minimize the exposed surface area. Mechanical covers show high potential for use on small reservoirs, stock tanks, and ponds.

Vegetation Management In and Near Surface Water.—Riparian zones constitute a small fraction of Western lands. They are significant to agriculture, however, and provide high-quality forage for livestock and are important in maintaining water quality. Many water experts believe that water "saved" by removing riparian vegetation remains in ground or surface waters for direct human use. However, **recent research indicates that plant removal from riparian zones does not necessarily make more water available for other immediate uses.** Consequently, less emphasis has been placed on vegetation eradication. Other technologies to manage riparian vegetation (e.g., chemical methods to slow plant-water use) are limited by high costs, unknown long-term effects on wildlife, and difficulty in application.

Aquatic plants present a special problem for irrigators because they interfere with water movement, disrupt control devices, cause leaks in canal linings, and lose water to evaporation at rates greater than would occur from open-water surfaces. As many as 85,000 miles of U.S. canals could be affected, and some water managers believe the problem is becoming more severe. These problems have a large economic impact.

Perhaps the most effective and least costly approach to aquatic-plant management is prevention. But where aquatic weeds are present, mechanical, biological, and chemical methods of control are available. Of these, the chemical methods are faster and easier; however, they involve problems of water pollution. Mechanical methods are expensive, time-consuming, and laborious, but are used by many water managers. Using biological methods—insects, fish, and plants—is rare but generally effective, economical, and minimally detrimental to the environment.

Technologies Affecting Soil Water

Many opportunities for improving soil-water conditions exist, both where precipitation is used to supply crop- and forage-water needs (rangeland and dryland agriculture) and where additional water is supplied to fulfill crop-water requirements (irrigation). Technologies that conserve precipitation include practices that shape the soil surface, manage the soil cover, and change the physical or chemical properties of soil. Technologies that supplement soil-water supplies include drip irrigation, surface irrigation, sprinkler irrigation, and subsurface irrigation. **Effective use of precipitation and irrigation water often requires the use of more than one technology and skillful management of plants, water, and soil.**

The extent of soil-water increase that can be expected with the adoption of a particular technology or set of technologies is difficult to quantify, given the wide variability in site conditions across the arid and semiarid region. Where water-conserving technologies are used on irrigated land, data that assess the effects of adoption on total water supplies are lacking. Similarly, information on economic and social consequences of technology adoption is generally not available.

Some water-conserving practices have been adopted by producers, but numerous barriers remain to their widespread application. First, many of these technologies are effective only under certain soil and/or climatic conditions. Where site conditions are not appropriate, application can yield little or no improvement in soil-water conditions. Second, some practices require large economic investments for equipment, fuel, and labor; application costs may outweigh their benefits in terms of higher farm or ranch profits. Third, the use of some technologies is hindered by Federal and State institutions. For example, mechanical land treatments on public rangelands by individuals are often prohibited; water saved by irrigators is often not allowed for their reuse. Finally, some practices are difficult to incorporate into existing farm and ranch operations and in some cases require new equipment or skills.

Soil salinization of irrigated lands and other effects of irrigation on natural resources (e.g., ground water depletion) lead many experts to believe that present irrigation agriculture is not sustainable and that existing practices will not make the contributions to agricultural growth that they have in the past. If a shift to limited irrigation or dryland or rangeland agriculture does occur, Western agriculture will face a period of economic and social readjustment which will be facilitated by development of a wide range of new opportunities for production.

Technologies Affecting Water-Use Efficiency of Plants and Animals

Agricultural production is handicapped on almost 35 percent of U.S. soils by either drought or salts, and much of this acreage is in the West. In the past, these lands were often ignored in the search for high-yielding crops that were adapted to more favorable conditions. The methods used to "improve" these lands—e.g., irrigation and drainage—are becoming less available and more expensive. Therefore, **technologies that improve the efficiency with which plants and animals use water, yet do not entail extensive additions of extra water, are likely to make large areas more productive.** These technologies include new and traditional methods of improving existing organisms as well as the use of plants and animals that have not been widely used in the United States previously or that are newly domesticated.

In arid and semiarid lands, the efficiency with which organisms use water has important implications for sustaining all types of agriculture, influencing the growth, distribution, and survival of plants and animals. Plants have evolved a number of different ways of coping with water shortages; no single factor completely controls the way plants respond. Plants may almost totally escape drought by germinating, growing, and reproducing before water becomes limited or only after a heavy rainfall. They may resist drought with special anatomical and physiological mechanisms to take up, store, and retain water. Or they may "tolerate" drought with mechanisms to limit the destructiveness of internal water deficits. The complex interaction of factors involved with these responses has slowed the development of drought-resistant agricultural plants.

Animals exhibit a similar range of adaptations to limited water supplies. Some may never drink water, obtaining moisture instead from their diet and excreting little water. Since the total amount of water used by animals is small, there has been little effort to use or breed animals that use less water. Instead, efforts have been concentrated on ways to increase the efficiency with which animals convert plant biomass into their own.

IMPROVING PLANTS AND ANIMALS WITH BIOTECHNOLOGY

Biotechnologies include intensive new methods of introducing genetic variation into bacteria, plants, and animals and reproducing the results. **Specific applications of biotechnology to the problems of water use in arid and semiarid lands are underway and are likely to increase substantially in the next 10 to 15 years.**

Tissue culture of rangeland, dryland, and irrigated crops is in commercial use and analogous methods are used in animal breeding. Protoplast fusion and recombinant DNA technologies are promising, but they face a potentially long period of basic research before being widely applicable.

Institutional constraints to biotechnology use exist in addition to the technical ones. There is concern that reliance on laboratory practices might narrow the genetic diversity of present crops to an undesirable degree. However, concerns regarding the release of novel, potentially dangerous, organisms have diminished. These technologies have already had important effects on agricultural research and have led to at least a short-term shortage of trained personnel. The fear exists that public sector agricultural research, handicapped by low funding and the inability to attract scientists, may not keep pace with private efforts and that there may be little progress in the application of new biological technology to problems of social importance with little foreseeable profit. **While much former skepticism has been allayed regarding the potential of biotechnology, such capital-intensive enterprises use relatively sizable amounts of public research money at a time when research funds are increasingly limited. Some concern exists that less glamorous technologies that also have significant potential—e.g., new approaches to classical plant breeding—will be overlooked.**

INNOVATIONS IN CLASSICAL PLANT AND ANIMAL BREEDING

Traditional methods of improving plants and animals will remain important. These techniques have accounted for yield increases of as much as 1 to 3 percent per acre per year for major annual crops. Range-plant breeding has been revitalized by the need for surface-mined land reclamation. Classical crop-plant breeding is likely to undergo an important shift in focus, however, as breeding for water stress becomes more important.

Identification of the character to be modified is the single most important step in plant breeding. It dictates both breeding and evaluation methodology. In many cases the fundamental mechanisms of adaptation to water stress are not known. Where critical features can be identified for breeding, they are often not based on more than a few genes, unlike the disease- and insect-resistant traits used successfully in past breeding programs. Thus, direct plant breeding for drought resistance awaits development of improved laboratory technology. Meanwhile, genetic markers can be used to correlate drought resistance with more readily measured features.

With adoption of the 1970 Plant Variety Protection Act and its 1980 amendments, institutional constraints to the development of new plant varieties decreased. Private investment increased, and larger numbers of new crop varieties were released. Concerns remain, however. First, the trend toward fewer, larger seed companies may have unanticipated effects on germplasm availablility. Second, the ownership of seed companies by agricultural chemical firms may foster breeding programs that increasingly rely on agricultural chemicals.

Production of meat, fibers, and other products by ruminants is an important and appropriate use of unique Western resources. Breeding programs increase animal productivity, sometimes by as much as 2 to 3 percent per generation. Embryo storage and transfer, artificial insemination, and computerized herd recordkeeping promise to accelerate increases in animal productivity.

Some animal-breeding technology is available only to large ranches with high incomes. Other methods promise to make important new germplasm available to small ranchers for the first time. **Major economic changes are occurring in the livestock industry, some of which are linked to the decreasing availability of inexpensive irrigated grains and forage. Shifts in the distribution of feedlots, the demand for red meat, and the relative importance of sheep and goats may have substantial implications for innovations in animal breeding.**

CHOOSING ADAPTED PLANTS AND ANIMALS

Many major crops and livestock species are not highly adapted to water stress, and their lack of genetic diversity may make Western agriculture overly susceptible to new pests or harsh conditions. **The broader use of native organisms and the domestication of new crops have potential for alleviating some of the environmental problems caused by agriculture in the past and for tailoring it more specifically to arid and semiarid lands.**

Promising crop candidates include amaranth, tepary bean, guar, cowpea, jojoba, guayule, saltbush, mesquite, buffalo gourd, and milkweed. These are food and fiber crops, biomass energy plants, or sources of industrial products. Their status varies widely. At least one, grain amaranth, may be poised for major entry into the agricultural market. Most others face major institutional hurdles: lack of an established market and infrastructure, disinterest from the established agricultural community, and incomplete research. Western agriculture may include "new" animals in the future, but the use of rabbits, elk, buffalo, and other species will probably not increase rapidly in the short term.

Salt-tolerant organisms may extend the agricultural life of areas that are naturally saline or that result from agricultural mismanagement. Adapting already salt-tolerant organisms for agriculture may be faster than adding salt tolerance to crops that now require freshwater. Salt-tolerant crops of the future may include algae, bacteria, and blue-green algae as well as higher plants.*

Technologies Affecting Ground Water

Ground water use in the Western United States almost tripled between 1950 and 1975, and the ground water percentage of the total water withdrawn in the region nearly doubled. Much of this increase in ground water use was made possible by technologies that permit the withdrawal of ever-deeper supplies at ever-faster rates, often in excess of recharge. This ground water "mining" has led to the noticeable depletion of ground water in many of the agricultural areas dependent on it. Technologies to recharge these supplies artificially depend on a water surplus during at least some portion of each year to use for recharge. Their effectiveness is also very site-specific, dependent on suitable geologic characteristics and availability of land where recharge ponds are to be used. **In some situations, ground water overdraft may cause the collapse (commonly referred to as "subsidence") of underground, water-bearing formations. This process renders them incapable of fully reabsorbing or transmitting recharge waters and causes displacement of surface structures.** In many of the areas most affected by ground water overdraft, the **total** available renewable water resources are being completely consumed each year.

Water quality among the major ground-water resource regions varies considerably with ground-water recharge rates, rock chemistry, and human waste-disposal practices. With the exception of portions of the Pacific Northwest and eastern Texas, the ground water of the Western States is moderate to very hard with high concentrations of calcium and magnesium salts. When water having high levels of these or other salts is brought to the surface and applied for irrigation, evaporation losses lead to increases of soil salinity. Irrigation return flows with high levels of dissolved materials and agricultural chemicals percolate back into the ground water, producing a further deterioration of the existing quality.

Once a ground water aquifer becomes contaminated, there is relatively little that can be done technologically and in a manner that is economically feasible to remove or contain the contaminant. A few technologies have been investigated for dealing with ground-water contamination problems, but in general these have been very expensive to implement and have produced uncertain results. Technologies effective against ground water pollution are those associated with surface and subsurface waste disposal designed to prevent contaminants from reaching the aquifer. **Control of toxic and noxious substances in surface and subsurface waters will probably remain the only feasible ground water pollution-control technology in the foreseeable future.**

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*Higher plants are those such as conifers and flowering plants, which possess a well-developed conducting system. Plants such as mosses, fungi, and algae are not part of this group.

While irrigated agriculture has consumed the largest volume of ground water in recent decades in the Western United States, municipal and industrial uses have also become increasingly important. Many Western cities are now dependent on ground water and have a greater stake in its quantity and quality. While irrigated lands may be shifted to a lower value use as water levels decline, cities cannot make this transition so easily. **The social costs of declining water tables and increasing contamination of ground water resources of the Western United States must be addressed as both an agricultural and a broader social and public health problem. Until more understanding has been gained, the most appropriate ground water technology may be prudent and conservative management.** It is probable that, in the long term, ground water may become much more valuable in some Western areas than is indicated by its present value for irrigated agriculture.

Selected Technologies Affecting Land and Water Management

Much Western agricultural land suffers from erosion, soil compaction, or other adverse changes, and these lands require improved management to restore their inherent productivity. In irrigated areas, improved water management may compensate for decreasing availability of affordable water.

Modern management technologies are developing rapidly and have potential for sustaining agriculture in arid and semiarid lands. They represent a wide combination of individual practices involving animals, plants, cultivation equipment, irrigation systems, and computers. Few attributes are shared: some are capital-intensive; others substitute labor for capital. Some are highly specialized, while others are diversified. At least two features are common. **The most promising technologies are based on an understanding of the operation and limitations of the natural hydrologic cycle, and they usually rely on significant amounts of information about the natural processes involved.**

WATER-MANAGEMENT TECHNOLOGIES

Water management includes flexible cropping, irrigation scheduling, water reuse, conjunctive use of surface and ground water, and crop enclosures. Several of these rely on relatively sophisticated methods of assessing soil and plant water requirements. Additional research is needed to validate the accuracy of some techniques. **More well-developed water-management technologies may not be available to managers because of high costs, a lack of trained personnel or suitable programs to transfer information to the producer, or the manager's inability to implement recommendations.** Federal policies may, in some cases, impose an additional constraint on technology adoption.

Reuse of municipal wastewater may represent a source of additional irrigation water and a possible method to reduce water pollution. Before this technology is implemented, however, questions must be resolved regarding its long-term effects on renewable resources and health. Legal, economic, and policy questions about ownership of reused water, its market value, and its allocation to uses besides agriculture must be answered.

Conjunctive use of surface and ground water may be technically feasible, depending on local geology and the extent to which ground water is manageable over a wide range of depths. It requires careful planning and the thorough understanding of local water resources.

Enclosures for plants and fish, especially those using solar energy, have potential for using unique Western resources, particularly the high amount of incoming solar radiation characteristic of the region. At present, they are suitable only for high-value agricultural products.

LAND-USE MANAGEMENT TECHNOLOGIES

With uncertain economic and resource conditions, such as increasing energy costs and unknown water availability, production specialization may involve increased risks. Therefore, **technologies that integrate different**

types of land use and different types of agricultural and nonagricultural products are especially promising for stabilizing economic risk. Land-use management technologies are diverse and reflect a range of agricultural philosophies. They include alternative agriculture, multiple land use on rangelands and farmlands, and animal mixtures on rangelands.

Alternative types of agriculture have largely unexplored potentials in arid and semiarid regions. These new systems may include complex mixtures of crops in one field, perennial grains or tree crops instead of annuals, or the elimination of synthetic pesticides and fertilizers. Generally, they rely heavily on natural biological processes.

Diversified farming and ranching have important benefits in areas where climate is unpredictable or the economy is unstable. Most types of land are amenable to some type of diversified enterprise; however, markets for products, restrictions on the use of public land, and specialization of agricultural production hinder adoption of these management systems. Increasingly, rangelands are used for multiple purposes. Some of these uses are not compatible with agriculture, and their effects on production and natural resources need to be considered.

The more complex management methods have received little research attention. These methods have potential for improving use of arid- and semiarid-land resources and for increasing farm income. In the past, interested private experimenters have often been isolated from one another, and this has hindered wide dissemination of knowledge about these practices.

COMPUTERS AND INFORMATION MANAGEMENT

Computers are having a major impact on agricultural extension services and on individual farmers and ranchers. They assist in recordkeeping and help prevent costly management errors. **Their role is likely to increase in the future, but questions remain regarding fair access to computerized information and the reluctance of many Western farmers and ranchers to adopt computer technology.**

POLICY ISSUES AND OPTIONS FOR CONGRESS

Agriculture as it is known today in the arid/semiarid United States is being increasingly threatened by water-related problems. Federal agricultural and water-related institutions are poorly prepared for the long-term needs brought about by these problems. Change is inevitable and in some areas is likely to be severe if current trends continue. Whether change ultimately produces a sustainable Western agriculture that strengthens the agricultural producer, the region, and the Nation depends in part on the role Congress chooses or declines to play in the coming few years.

Theoretically, future congressional action might range from delegating all control over water resources to States and regions to preempting State laws completely and nationalizing the water resource. Israel's successful national water-management program is based on this latter action, providing a national focus and goal with respect to water. More likely, appropriate actions for Congress lay between these extremes. For example, this Nation has neither a comprehensive national water (surface and ground) policy nor a national agricultural policy. As limits are reached and long-term productivity is threatened in the West, Congress may be asked to decide whether it will, acting for the Nation, develop an effective national water policy or whether States and regions will be left to fill the vacuum in water-resources management and planning. The actions chosen will depend on the level of this Nation's commitment to protecting the long-term productivity of its renewable resources.

However, Congress alone cannot act effectively in this complex and diffuse area. Federal, State, and local governments are all involved in the regulation of Western water, for agricultural and other uses, and thus affect use and development of water-related technologies for arid/semiarid agriculture. The broad types of Federal tools available to influence use and development of these technologies involve institutional action to develop an improved statement of goals and priorities for Western water use and agriculture, provide incentives, penalize abuses, promote improved management, equitably resolve conflicting claims and demands, and provide more and improved information.

In recent years, awareness has increased that most of the West's water-resource problems transcend State boundaries and are extremely difficult in nature, involving a complex web of physical, chemical, biological, economic, legal, and sociopolitical issues. Often, they go well-beyond the ability of a single agency, State, university, or group of organizations to address effectively. Western States have begun to take impressive steps to increase their role in regional interaction and water-resources planning and management (see examples in app. C). However, they cannot handle all the problems alone. The need for an active Federal commitment to water-related matters of broad public concern and wide geographical jurisdiction has become increasingly evident for sustainable Western agriculture.

The following policy issues and options have been identified by OTA as those most critical for congressional action over the next few years. They are grouped in three major categories (treating renewable resources as systems, sustaining long-term productivity, and involving users in decisionmaking) to parallel the three fundamental findings of this assessment. They are not listed in any order of priority.

Treating Renewable Resources as Systems

This major action area is divided into three categories:

1. how Western scientists, water users, universities, and the public-at-large can play an expanded role in decisionmaking about water and Western agriculture;
2. how congressional decisionmaking can be strengthened; and
3. how other Federal and State Government agencies can improve specific programs.

Issue 1: The Need for an Interdisciplinary Program of Basic and Applied Research on Arid/Semiarid-Water Resources

The Nation's universities, water users, and private sector have a variety of research programs on water resources and water-resource management and could provide unique services in arid/semiarid-water resources research and decisionmaking. At present, however, links are often not made to broader national or regional problems and there is a lack of a national coherence and synthesis of university water-related research. Progress in Western water-resources research, both basic and applied, could benefit substantially by the creation of a broad coordinating mechanism to focus and interrelate the multidisciplinary talents of the academic community and water users with the resources of the private sector. The Nation's universities are especially important to tap at a time when Federal assistance to coordinate water planning and research has effectively disappeared.

Option: Congress could establish a National Center for Water Resources Research to provide a coherent and coordinated mechanism for the Nation's university research programs in water resources and water-resource management for problem-solving and policymaking.

The mission of this center could include:

1. Undertaking an interdisciplinary program of basic and applied research on water resources and water-resource management, including strong programs in the natural sciences, engineering, and social sciences, such as resource economics and law as they pertain to water-resources programs. The center could further assist in the conduct of site-specific research being carried out under State auspices.
2. Developing and providing advanced and sophisticated research facilities on a scale required to cope with the broad nature of water-resources problems, and often not affordable by single universities, to be used by resident staff, innovative producers, and university scientists.
3. Undertaking a program to develop and test conventional and emerging technologies for application to water-resources problems in United States arid/semiarid lands, including problems of agriculture and its sustainability in arid/semiarid lands, and coordinating such efforts with existing government research by USDA and State agricultural experiment stations.
4. Serving as an objective, nonpartisan, and continuing national source of information for Congress when formulating public policy dealing with water resources, and as a link to public agencies, water users, and the private sector for application of research findings.

This center could serve as a base for marshaling university and private industry talents and for augmenting, but not in any sense competing with, university work already underway. Using the successful experience of the National Center for Atmospheric Research (NCAR), an institution created some 20 years ago by an act of Congress, the center could be managed and operated by a consortium of universities with doctoral-level programs in water resources. An essential aspect for effective operation is that prime responsibility for program initiatives reside with this consortium. This requirement is in sharp contrast with "Government owned-contractor operated" laboratories where program initiatives commonly reside in the sponsoring, mission-oriented Federal agency. This contrasting approach for the center is important, since the university community is closest to the research and its potentials. In light of this knowledge, plans and priorities designed by the consortium would take into account national, regional, and State needs.

Issue 2: The Need for Congress to Have Reliable Ongoing Information About the State of the Nation's Renewable Natural Resources

The assessment finds that existing data available for congressional decisionmaking is scattered throughout the Federal Government in a variety of forms. These data were not collected with the intention that each piece would be part of an integrated and self-consistent base for Congress to use in making decisions affecting resource sustainability. Moreover, existing data on components of the resource base on which agriculture depends are seldom synthesized because the data may be in noncompatible forms and no single agency has had the ongoing responsibility to seek compatibility or synthesis.

Congress needs improved information for setting near- and long-term goals for sustainable use of Western water and agricultural lands. This information should focus on congressional needs and emphasize systems analysis of the natural resources on which agriculture depends. Ongoing analysis and synthesis of existing data bases could provide improved information on the dynamics of the resource system and how interactions (natural and manipulated) among resource components affect the sustainability of Western agriculture.

Option 1: Congress could develop a bipartisan unit within the legislative branch with the principle purpose to provide Congress with ongoing quantitative evaluations of the state of the renewable natural resource system as a consequence of near- and long-term congressional policies. The unit's program should be interdisciplinary and multidisciplinary, with access to state-of-the-art computer facilities to conduct comprehensive data analysis and synthesis from existing data sources on specific topics requested by Congress. Such a unit could identify data gaps important to U.S. decisionmaking that affects the sustainability of the renewable resource base. It would require independence and flexibility to obtain and interpret data in a nonbiased fashion for the entire Congress. Specific organizational structure and legislative authority would have to be developed to meet the unit's defined purposes.

The first step in considering this option might be a workshop of interested and involved congressional, executive, State, and local participants to examine existing problems, the history of similar attempts and experiments in data synthesis, and possibilities for action. This workshop might be combined with the formation of a joint committee of members from relevant House and Senate committees to plan subsequent steps.

This option will require ongoing communication among the many branches of Government to acheive an acceptable arrangement for the new unit. Some individuals within Congress and the executive agencies may question the value of such a unit for a number of reasons. In recent years, public concern has increased over the growing size and cost of congressional staffs. Others may claim that existing agencies are competent and qualified to provide Congress with the resource systems analytical capacity.

Option 2: As an alternative to option 1, Congress could develop an executive branch unit to provide ongoing quantitative evaluations for congressional decisionmaking affecting resource sustainability. On congressional request, this unit could coordinate, integrate, and interpret existing information similar to that noted for the legislative unit proposed in option 1, and report directly to Congress. Traditionally, Congress has turned to the executive branch for answers to fundamental questions involved with its policymaking. Existing executive agencies have personnel, equipment, and many separate data bases; some career staff have experience in aspects of water- or agricultural-data collection and analyses. Partial funding might be available for this option through redirection of existing funds from lower priority executive activities, as determined by Congress.

Possible disadvantages of this option relate to the adequacy of existing agencies to incorporate this function and the nature of executive branch programs in general. The capacity of existing executive agencies for long-term and multidisciplinary resource systems planning is seriously lacking. The placement of this systems capacity in the executive branch poses concerns about continuity. Programs and priorities in the executive branch change with administrations. A small new executive unit is unlikely to be in a secure position to provide objectivity, coherence, and continuity, essential requirements for effective long-term data syntheses. In recent years Congress has found it necessary to develop inhouse expertise to supplement executive branch input in areas requiring focused analysis, integration of issues or activities, and verification or clarification of executive branch reports.

Issue 3: The Need to Integrate Water-Related Agricultural Activities in Government Agencies

Increased demands are being placed on the arid/semiarid-agricultural resource base as pressures grow from new and expanding water uses. The complexity of the natural processes in arid/semiarid agriculture requires an integrated approach to resource manipulation in order to cope effectively with these increasing demands and to ensure a sustainable agriculture. No longer can Western water-related agricultural problems be trusted to one-problem/one-solution procedures that have been relied on chiefly in the past by government institutions.

Federal agencies charged with implementing congressional policies and programs need a perspective that interrelates technological impacts as they affect various components and ultimately the agricultural system and long-term productivity of the region. The following options are specific areas conducive to immediate congressional action. All four are compatible.

Option 1: Congress, through the hearing process, could initiate discussions with USDA for the purpose of designing and establishing a high-level office to integrate and provide coherence to water-related and agricultural activities within the Department. This office of resource coordination should be placed at an appropriately high level—e.g., in the Office of the Secretary of Agriculture—to minimize confusion in organizational responsibilities and to ensure coordination and integration of activities among all specialized agencies of the Department. This office could have responsibilities for analyzing programs of the specialized agencies, for helping formulate a systems perspective that integrates the agencies' resource programs, for minimizing narrowness of focus and potentially conflicting activities, and for overseeing implementation of integrated programs in research, technology development, and production in long-range sustainable arid/semiarid agriculture. An office at the level of the Secretary could emphasize the importance of agriculture's natural resource base and make visible the role of the Department in protecting it. It could encourage the Department to take advantage of the most modern systems-analysis technology, technology that has not commonly been used in agriculture.

Option 2: Congress could instruct Federal land-management agencies responsible for Western areas to increase efforts in water resources and water-resources management pursuant to their existing multiple-use responsibilities for managing natural resources on public lands. Existing multiple-use statutory guidelines prohibit optimization of single measurable uses (e.g., timber and cows) at the expense of less quantifiable uses (e.g., watershed and recreation), and they forbid practices that impair long-term land productivity. This option will entail a reorganization of agency priorities such that more emphasis is placed on long-term benefits from water management and less emphasis is placed on short-term revenue-producing benefits from grazing and timber production. This is an area of considerable importance for long-term Western water-resources management and arid/semiarid agriculture because most Western surface water-producing areas are on public lands.

Option 3: Congress could assist States to develop and integrate computerized data bases for the wide range of hydrologic data now scattered among State and local agencies and private industry. Such information is not being entered into Federal data storage systems but is increasingly needed for effective water-resources planning and management at the regional, State, and local levels. Data bases could be designed to ensure integration of water quality and quantity data for systems planning. Federal funds to States for water-resources planning and coordination could be allocated for State participation in this data system. The private sector could share data and give advice on the best available technology for data storage, retrieval, and processing.

Option 4: Congress could expand mandates of Federal agencies responsible for water-project development and maintenance to take into account needs of instream flow, a subject that has had inadequate and, in recent years, reduced attention at the Federal level. Some minimum instream flow requirements are essential for rivers for dilution, hydroelectric generation, and fish and wildlife habitat protection. In many river systems of the West, however, virtually the entire flow of the river is committed already to various offstream uses. In view of the geographic nature of river systems, an increased Federal role is needed to help define and monitor instream flow requirements of Western rivers. The maintenance of instream flows may make it possible to maintain acceptable water-quality levels in some Western rivers without the need for greatly increased water-treatment facilities. An improved understanding of instream needs for the multiple purposes of Western river systems will also improve management information for planning long-term requirements of the various water users.

This option may raise additional burdens as well. Traditionally, the Federal Government has deferred to the States on matters involving local water rights. Virtually the entire flow of many Western river systems is committed already to various local offstream uses. If instream flow requirements are to be met on these rivers, some existing offstream uses might have to be curtailed or discontinued. Federal involvement will raise all the difficulties inherent in trying to coordinate and respect these two governmental systems, the longstanding States' interests in local water rights and the broader geographic and national interests of the Federal Government.

Sustaining Long-Term Productivity

Issue 1: The Need for a Strong Federal Role in Water Quality for Sustainable Western Agriculture

Congressional action to maintain strong water-quality standards, support pollution controls, and strengthen water-quality research is essential for protecting agriculture, the environment, and the public health of the arid/semiarid West. Because of the West's low or sporadic water-volume flows, the region cannot absorb the levels of industrial, municipal, and agricultural pollution possible for more water-abundant regions. Without the maintenance of a strong and committed Federal role, it is conceivable that agriculture in some areas may go out of production because of water-quality degradation rather than loss of supplies.

Three options are particularly important, and all are compatible for immediate congressional action.

Option 1: Congress could maintain a firm commitment under the Clean Water Act to strong water-quality standards that are applicable across the Nation in order to ensure that economic burdens and benefits are evenly shared among States and to avoid industrial "shopping" for areas where water-quality standards might be low. National water-quality standards must be stringent in order to protect the range of present and future interests in water, some of which require the highest standards (e.g., for drinking-water purposes). Existing requirements could be retained, and any new or revised water-quality standards could be made to enhance the quality rather than allow degradation.

Option 2: Congress could refine national nonpoint source policy under the Clean Water Act and particularly under section 208 of that act, and accelerate implementation of controls on water pollution from nonpoint agricultural sources. Knowledge exists to reduce water pollution from agricultural nonpoint (diffused) sources through the adoption of improved management practices. Some of these practices may involve costs that are difficult for economically disadvantaged farmers and ranchers to absorb over the near term. However, such costs may be far outweighed by long-term benefits in reduced water-treatment costs and public health problems and thus justify Government assistance with implementation. As part of this action, Congress could strengthen Federal support to State and local efforts to achieve nonpoint source pollution reduction. Because the water-short Western States face more concentrated contamination possibilities with any pollutant, progress toward implementing control programs is essential. Increased Federal support could come in a number of forms, including providing incentives, assisting economically depressed farmers to adopt better practices, and offering technical and financial assistance for training farmers and ranchers to implement control measures.

Option 3: Congress could increase research and monitoring of short- and long-term agricultural and public health effects of Western surface and ground water-quality deterioration. Little water-quality research has been undertaken on a comprehensive areawide basis or on related health and environmental impacts of water-quality degradation. Existing standards may not adequately protect the public in some areas, while others may be too stringent. In view of the West's low or sporadic water-volume flows, the prudent approach is to maintain high or more stringent standards for both surface and ground waters and to support high levels of water-quality research to ensure long-term protection of the public health and of the environment on which agriculture depends. Particular focus could be given to synthesis of existing information, most of which is scattered and contaminant-specific, and to research on likely agricultural contaminants that are detrimental to other uses and on contaminants from other uses that are detrimental to agriculture. Such activities could provide valuable information for national and local policymaking to protect ground waters and surface waters from contamination.

Issue 2: Protecting and Maintaining the Long-Term Productivity of Rain-Fed Agricultural Resources

Protecting the renewable resource base for productive rain-fed agriculture in the arid/semiarid West is a growing national concern, especially since irrigated production in some areas is likely to decrease because of water problems. Two areas, in particular, have received inadequate Federal attention in the past. First, the problem of cultivating marginal or unsuited lands ("plow-out") has become particularly critical in the semiarid lands of the Great Plains and in other States in the West where the land is especially vulnerable to erosion. Some Federal agricultural programs encourage cultivation of fragile lands and thus contribute to resource degradation. Second, dryland and rangeland research and technology development have received scant Federal support. This area is particularly important for expanding the range and mix of opportunities for productive Western agriculture on rain-fed agricultural lands over the long term. The following two options are important and compatible.

Option 1: Congress could withdraw those Federal programs that induce conversion of rangeland to uses not suited to that land and thus cause resource degradation that ultimately limits long-term productivity. One method of achieving this could be to require that applicants for Federal agricultural assistance certify that their land is not new cropland or, if so, to demonstrate that a conservation system approved by the local conservation district is, or will be, in place for the land to be put into production. The land-capability classes could be used as a guide for determining what lands are unsuited for cultivation and thus ineligible for Federal assistance, except with an approved conservation plan.

Option 2: Congress could direct that USDA increase its R&D focus on rain-fed agricultural systems—both dryland and rangeland. Significant opportunities exist to develop and expand dryland and rangeland research into broader areas of focus than now exist. Increased support is needed if this Nation is to have the range of alternatives necessary to ensure flexibility in meeting anticipated and unanticipated future needs for agricultural production in the West. As one means of implementing this option, Congress could hold hearings with USDA to examine that Department's existing field research stations. The purpose would be to identify and convert appropriate stations to facilities for testing and developing technologies, based on an integrated resource approach, to sustain or improve rain-fed agricultural productivity of these arid/semiarid lands over the long term. The work could be made readily available to producers through special pilot projects and field-days and through the conventional extension programs.

Involving Users in Decisionmaking

Issue 1: Achieving Equity in Western Water Availability and Distribution

Lasting settlement of conflicts over Western water use must involve principles of equity and fairness for current users, for those whose rights have yet to be developed, for those whose communities and lifestyles might be affected by major water shifts, and for new users with economic power who seek to buy water supplies. Already, perceptions are growing among poorer farmers and American Indians that existing Western institutions responsible for water distribution and development have not treated them fairly. Without committed congressional action, conflict, distrust, and litigation will probably increase and will severely hinder effective water-resources planning and management for sustainable Western agriculture. Two kinds of congressional actions are important and compatible here.

Option 1: Congress, in its leadership role with reserved water rights, could increase its efforts to address the complex long-term task of resolving issues surrounding Indian reserved water rights under the Federal reserved rights doctrine by taking two initial actions: 1) increase opportunity for ongoing representation of Indian interests in both Houses of Congress, and 2) provide a mechanism through legislation to protect reserved rights and equity interests where the rights are already fully appropriated; that is, by compensating the reserved rightholder and by eventually reallocating the water to that rightholder. Because Congress has consistently left these issues unresolved, piecemeal court decisions have increased uncertainty for all parties, and important Federal interests and economic investments have been threatened. Resolving reserved water-rights issues is an essential step in the effective long-term planning and development of sustainable Western agriculture. Congress might consider a variety of approaches to increase its activity in negotiation and representation of Indian water interests including the appointment of a joint House and Senate committee, a special committee or task force to define more clearly appropriate future action, or creation of an ongoing subcommittee on Indian affairs.

Option 2: Congress could help to ensure that equity and fairness are elements of any water-resources distribution and reallocation decision for disadvantaged people, especially poorer farmers, by establishing a Select Committee on Disadvantaged People and Renewable Resources to investigate and recommend legislation to protect these interests. Among the topics the committee could address are mechanisms for: 1) educating Western disadvantaged people about their stake in water management, and 2) bargaining collectively for Western water rights that may be bought or sold in a market framework. Such mechanisms could be important in helping disadvantaged people increase participation in water-use and reallocation decisions in the arid/semiarid region. They could thus have a more effective voice in Western decisions involving major water-use shifts that are likely to have significant impacts on local lifestyles, economies, and community patterns.

Issue 2: Understanding the Impacts of Water Prices on Adoption of Technology

Federal reform of water-project repayment plans and policies is underway. Reduced Federal subsidies will make Western water more expensive for all users. Impacts on agriculture, a major water user, could be significant. Some agricultural users may become more efficient in water use by adopting water-"saving" technologies, while others may decide they cannot operate profitably and will attempt to transfer (sell or rent) their water rights. The outcome for agriculture is not well understood or studied. To help ensure that reforms produce desirable results, a careful study and documentation of existing markets and anticipated agricultural consequences is needed.

Option: Congress could seek the assistance of the Congressional Budget Office (CBO) to study the short- and long-term economic consequences of reduced Federal water subsidies and increased water-market activity on agricultural users and others affected by agriculture. A CBO analysis could help Congress: 1) understand the possible near- and long-term economic consequences of reforming water-project repayment plans and programs for Western agriculture and nonfarm economies; and 2) provide guidance, monitoring, and assistance with the transition to greater use of water markets to the extent that is likely to result from reduced development subsidies. While scattered studies are beginning to appear on the economics of water in the West, CBO could provide an objective, comprehensive synthesis of available socioeconomic information and a focused analysis of the Federal connection with the economics of Western water and agricultural practices.

Issue 3: Improving the Effectiveness of Water-Related Technologies for Sustainable Agriculture

Development and successful application of water-related technologies depend, in part, on the ability of the researcher and user to adapt them to local conditions. This is a result of the complexity and spatial and temporal variability of the natural resource system on which agriculture depends. In addition, the researcher's perspective about effectiveness may vary from that of the user. The former may be concerned with technical efficiency, while the latter is interested in economic efficiency for farm or ranch use. A gap appears to be growing between the researcher and user of water-related technologies in Western agriculture in some areas. Research for both onsite and offsite technologies commonly suffers from questions of relevance and practicality for a particular agricultural site and user.

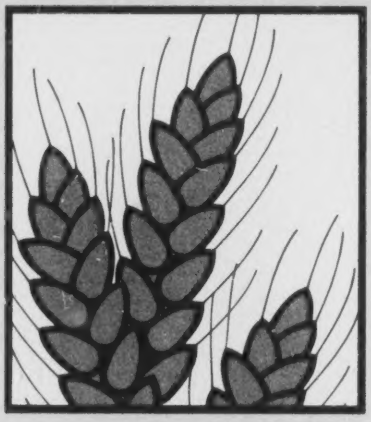
Option: Congress could direct the establishment of two user oversight groups specifically focused on Western water and agriculture. One user group could address onsite water-conserving technology potentials and needs and provide advice principally to USDA. The other user group could focus on offsite water augmentation technologies for downstream agriculture. This second group could advise Federal agencies responsible for those water-related technologies (e.g., weather modification, watershed management, snowmelt forecasting) applied upstream or in highland areas offsite from arid/semiarid agriculture but having potential water-related impacts for downstream or low-land agriculture. Each user group could advise appropriate congressional committees as well.

By making use of innovative producers and by bringing the research to the farm or ranch, this option could improve research/user interaction, an essential aspect of effective technology development and adoption now seriously lacking in many areas. User groups could assist Congress to determine whether existing programs are doing the job needed for sustainable agriculture from the Western users' perspective.

Concerns about this option relate to the possible effectiveness of the user groups. At present, a National Agricultural Research and Extension Users Advisory Board (UAB) exists pursuant to legislation in the Food and Agriculture Act of 1977. A recent OTA report* on the food and agricultural research system found this board's effect on USDA research priorities to be unclear. Other concerns are that researchers who interact with user groups would be taking time that might be spent otherwise with laboratory or field work. Moreover, the focus of particular users might be on short-term economic solutions rather than long-range issues involved with the development of technologies for sustainable agriculture.

Precautions in establishing these groups will be required to ensure that they effectively represent the range of users' views, include long-range interests, and have the capacity to evaluate and scrutinize Federal agency research work. Congress could require that users be nominated by representative agricultural organizations and have access, when necessary, to scientific expertise independent of the Federal agencies. Membership rotation could ensure a flow of new ideas to minimize loss of research time on new potentials.

**An Assessment of the United States Food and Agricultural Research System*, OTA-F-155, December 1981.



II

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Chapter II

Agricultural Production in the Western United States

Throughout the history of the United States, agriculture has helped shape the Nation's people, prosperity, and outlook. Self-sufficiency in agriculture served to transform a rural, agrarian society into a largely urban, industrial one. Internationally, American agriculture played a vital part in supplying food to those in need during periods of crises such as war, crop failure, and famine.

Today, agriculture continues to supply an abundance of relatively low-cost food and fiber to domestic consumers. Agricultural exports, in recent years, have been especially valuable to the domestic economy by creating a trade surplus to offset, in part, the deficit in some nonagricultural trade accounts. Agriculture also provides a livelihood to workers directly involved in agricultural production and in related industries such as food processing, farm equipment manufacture, and transportation of agricultural goods.

Arid and semiarid lands comprise about one-third of the contiguous United States and are an integral part of the Nation's productive capacity. Particular qualities of the area make it especially suited to certain types of agriculture. The climate, characterized by low humidity and many cloud-free days, is ideal for some irrigated and nonirrigated crops such as wheat, sorghum, cotton, potatoes, barley, and specialty crops such as fruits, nuts, grapes, and table vegetables. In some areas where the growing season is long, farmers can produce crops throughout the year. Seed and nursery stock production are also well-suited to the arid and semiarid region because the area's dry climate discourages growth of plant pathogens.

The arid and semiarid region is well adapted to animal production as well. Large acreages of land not suitable for intensive cultivation provide low-cost forage for animals that are used for meat, hides, or wool.

In addition, Western agriculture extends the diversity of agricultural production in the Nation and further ensures that domestic consumers have a reliable and varied food supply. Moreover, it is an important component of many local economies and contributes to the perception of a Western lifestyle. Many production technologies originated in U.S. arid and semiarid regions and were then transferred to more humid areas or to other countries. Finally, in an age of increasing urbanization, the wide expanse of open land, characteristic of the region, offers visual amenities and numerous recreational opportunities and supports a diverse and unique population of native plants and animals.

Many forces threaten continued success of this country's agriculture, but one factor that particularly threatens Western agriculture is limited water. Water is essential for food and fiber production, yet in much of this region, low precipitation limits both plant survival and growth. On land where precipitation is supplemented by water application, increasing competition from municipal and industrial users, diminishing ground water supplies, higher pumping costs, and declining water quality cloud the future of agriculture.

This chapter describes the character of Western agriculture and discusses its present features and future outlook. Other chapters address the water issue explicitly as it relates to agriculture.

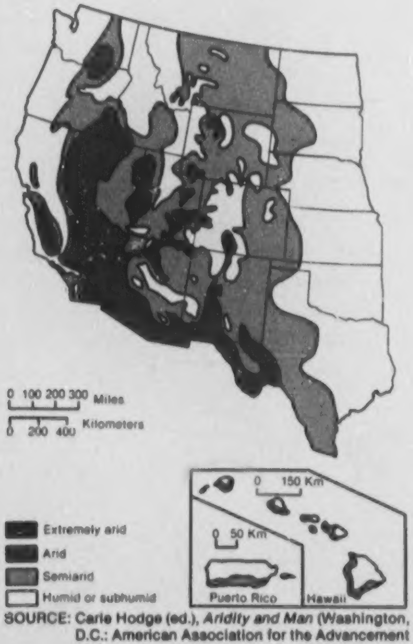
CHARACTERISTICS OF ARID/SEMIARID LANDS

No universal definition of arid and semiarid lands exists for agricultural purposes. Definitions based solely on total annual precipitation fail to provide adequate information on its distribution throughout the year and on other climatic elements—e.g., temperature, humidity, wind, and intensity and duration of sunlight—that characterize the arid and semiarid environment. Definitions based on vegetation types, soils, animal distribution, or land use are similarly limited in application. Arid and semiarid lands, as used in this assessment, are those lands where crop-water requirements exceed the plant-available water (growing season precipitation plus soil water stored in the root zone) by a significant amount.

Arid and semiarid lands characteristically have predominantly clear skies, high average wind speed, and low relative humidity. The average annual precipitation is generally 20 inches or less. In the continental United States, the arid and semiarid area includes parts of the 17 Western States that lie between the 100th meridian and the Sierra Nevada and Cascade Mountain ranges (fig. 4). Offshore are scattered arid and semiarid areas on the Hawaiian Islands, the Virgin Islands, and Puerto Rico. In this assessment, the arid/semiarid lands of principal focus will be those located in the 17 Western States.*

Table 2 presents the land area by State for the 17 Western States. Because information on agricultural production is tabulated and classified by State boundaries, production figures for some areas (particularly in the Pacific and Great Plains regions) include crops and livestock produced under humid and subhumid conditions.

Figure 4.—Arid and Semiarid Regions of the United States



SOURCE: Carle Hodge (ed.), *Aridity and Man* (Washington, D.C.: American Association for the Advancement of Science, publication No. 74, 1963).

Table 2.—Agricultural Land in the Western States, by State, 1978

State	Total land area (rounded to million acres)	Agricultural land (percent of total)
Great Plains:		
Nebraska	49	93
North Dakota	44	91
South Dakota	49	89
Kansas	52	89
Texas	168	80
Oklahoma	44	74
Mountain region:		
Wyoming	62	78
Montana	93	70
New Mexico	78	69
Nevada	70	67
Colorado	66	60
Arizona	73	59
Idaho	53	52
Utah	53	49
Pacific region:		
Oregon	62	46
California	100	35
Washington	43	35
17 Western States	1,158	67
31 Eastern States	739	38
Total	1,897	56

Note: Agricultural land includes cropland, grassland, pasture, and range.

SOURCE: H. Thomas Frey, *Major Uses of Land in the United States: 1978*, U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 487, 1982, appendix table 1.

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*Although some resource management and technology aspects of this assessment apply generally to any arid or semiarid situation, islands have unique natural resource characteristics and agricultural capacity that vary by location and geology. A separate study of arid and semiarid islands is suggested.

FEATURES OF WESTERN AGRICULTURE

Natural features, including climate and weather patterns, soils, topography, and vegetation, differ markedly across the West. These natural features, in turn, influence the types of agriculture that are practiced and the crops that are grown.*

Western Agriculture in the National Context

Agriculture (farming and ranching) is the dominant land use in the Western United States. On average, the 17 Western States use about 67 percent of the land for agriculture compared with 38 percent in the East. This percentage changes across the region and ranges from about 90 percent of the land area in some States of the Great Plains to less than 40 percent in California and Washington (see table 2).

Unlike the Eastern States, a substantial amount of land in the West is federally owned (table 3). This percentage varies widely. In Nevada, for example, over 85 percent of the land is federally owned. In contrast, approximately 1 percent of the land in Kansas and Nebraska is federally owned. Much of the public land is used primarily for livestock grazing; a smaller portion is used primarily for timber production, recreation, mining, or national security installations.

Products of Western agriculture constitute a large share of the total income derived from farming in the United States. In 1980, cash receipts from marketing livestock and their products and crops in the 17 Western States accounted for approximately $59.3 billion, or about 43 percent of the income derived from farming in the United States (table 4).

The types of agricultural goods that produce this income vary across the region and include livestock products (e.g., meat, wool, hides, milk, eggs, genetic material) and crops such as wheat, barley, sorghum, cotton, hay, vegetables, field seed crops, fruits, and nuts. Within the arid and semiarid area, there are regions of crop specialization. In eastern Washington

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*Appendix A presents more information on natural features, and agricultural production in the arid and semiarid region.

Table 3.—Ownership of Land in the 17 Western States

	Ownership		
	Federal (000 acres)	Non-Federal (000 acres)	Percent Federal
17 Western States	368,108	789,503	32
31 Eastern States	33,759	704,693	5

SOURCE: U.S. Department of Agriculture, Soil Conservation Service, *1977 National Resources Inventory, Basic Statistics*, revised February 1980, table 1.

Table 4.—Cash Receipts From Farm Marketings, 17 Western States, 1980[a]
(million oollars)

	Agricultural product		
State	Livestock and products	Crops	Total
Total, 17 Western States	$30,281	$29,058	$ 59,339
Total, United States	$69,209	$68,806	$138,015

[a] Other income derived from farming (e.g., Government payments and nonmoney income) are not included in totals.

SOURCE: U.S. Department of Agriculture, Economics and Statistics Service, *Agricultural Outlook*, March 1981, AO-63, p. 25.

Photo credits: USDA-Soil Conservation Service

Western agriculture

Box B.—Numbers, Numbers, Numbers

Congress, executive agencies, States, farm organizations, and the public rely on agricultural statistics compiled by numerous Federal agencies. One of the most well-known and widely used sources of a variety of agricultural data is the Census of Agriculture, conducted every 5 years by the U.S. Department of Commerce, Bureau of the Census. Among the statistics that the census collects are: land use, number of farms, crops harvested, average size of farms, characteristics of farmers, and farm production expenses.

The U.S. Department of Agriculture (USDA) also has a major responsibility for collecting and tabulating information on soil and water resources, land use, world agricultural production and trade, farm income and expenses, crop supplies, market prices, and crop use. Much of this information is gathered independently by various agencies within the Department, but some data are supplemented and coordinated with the Census of Agriculture and statistics from other executive departments.

The large amount of agricultural data and the number of organizations that collect information have led to some problems for data users. First, coordination of data between organizations that collect similar information is sometimes difficult. Second, there is often a delay between the time the survey is taken and when it is compiled, summarized, and published. Another problem is the accessibility of information. Agricultural data are dispersed throughout various USDA agencies and other departments. USDA makes an effort to compile these statistics, and each year the Department publishes *Agricultural Statistics.* Information, however, focuses on agricultural commodities. Data on cropland and rangeland use, conditions of soil and water resources, and other natural resources must be obtained from other sources, both within USDA and outside the Department.

Finally, there are problems related to the nature of agricultural surveys. Data are collected and tabulated along political boundaries, and it is very difficult to evaluate agricultural production under arid/semiarid conditions v. humid/subhumid conditions in States where both climatic types exist. Both the census and USDA have been criticized also because of the scope of their surveys. For example, neither collects information on the extent of some agricultural practices such as organic farming, "new crops," and livestock operations on public lands.

and Oregon, Idaho, and the Great Plains, for example, large acreages of wheat, sorghum, and barley exist. In California and other irrigated areas, farmers grow a wider mix of products, including specialty crops such as table vegetables, citrus fruits, wine grapes, and melons, and row crops such as corn and cotton. Wyoming, Colorado, Nevada, and Utah derive a major portion of their agricultural income from cattle and other livestock and their associated products.

Certain crops grown in the West constitute a significant share of the total acreage and value of that crop for the entire Nation (tables 5 and 6). For example, nearly 85 percent of all

Table 5.—Selected Major Crops Harvested in the 17 Western States, by Acreage, 1978

Crop	Acreage (000 acres)	Percent of national production
Wheat for grain	46,811	86
Hay crops	29,116	47
Corn for grain or seed	13,870	20
Sorghum for grain or seed	11,620	90
Cotton	9,260	73
Barley for grain	7,512	84
Oats for grain	4,487	44
Land in orchards	2,635	58
All vegetables harvested for sale	1,647	40
Field seed crops	905	65
Irish potatoes	867	62
Strawberries	21	46

SOURCE: U.S. Department of Commerce, Bureau of the Census, *1978 Census of Agriculture*, vol. 1, ch. 2, tables 29-34, 1981.

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Table 6.—Market Value of Major Agricultural Products Sold, 17 Western States, 1978

Crop	Value (million $)	Percent of national market
Livestock, poultry, and other animal products	$27,461	46
Wheat for grain	3,947	83
Hay crops	2,981	46
Fruits, nuts, and berries	2,834	61
Corn for grain or seed	2,689	19
Cotton	2,657	78
Vegetables, sweet corn, and melons	1,973	60
Field seeds, hay, forage, and silage	1,343	58
Sorghums for grain or seed	1,123	87
Irish potatoes	840	68

SOURCE: U.S. Department of Commerce, Bureau of the Census, *1978 Census of Agriculture*, vol. 1, ch. 3, compiled from individual State tables, 1981.

land used for wheat, barley, and sorghum production in the United States is located in the 17 Western States. Most of the agricultural land used for the production of cotton, orchard crops, and field seed crops is also located in the region.

Export markets, particularly those in Japan and other countries in the Far East, provide a significant source of income for Western producers and represented about 30 percent of cash receipts from farm marketings and about 40 percent of the total U.S. agricultural exports in 1980 (table 7). The leading Western States in terms of income derived from agricultural exports are: California, Texas, Kansas, Nebraska, and North Dakota. California, Texas, Kansas, and Nebraska are also among the top 10 exporting States, by value, in the Nation. Texas, for example, ranked first by value in exports of cotton, grains, tallow, cattle hides, beef, and live animals in 1980.

Western agriculture also generates employment in processing operations such as canning, packing, and ginning, and in support services such as equipment sales, transportation, and farm and ranch supply businesses (table 8). Many of these enterprises are rural-based and are an important element of rural life (see discussion of rural economies and agriculture in ch. V).

Table 7.—Agricultural Exports in the 17 Western States, by Value, October-September, 1979-80 and 1980-81 (million dollars)

Region	1980	1981
17 Western States	$16,662	$17,656
Total United States	$40,481	$43,789
17 Western States, percent of United States	41%	40%

SOURCE: U.S. Department of Agriculture, Economic Research Service, *Foreign Agricultural Trade of the United States*, March/April 1982, table 17.

Types of Agriculture in the Arid and Semiarid Region

Agriculture is shaped by the natural environment—landscape, climate, and soils. Production technologies, landownership patterns, distance to livestock and crop markets, economic conditions, individual choice, and social custom also influence agricultural production.

Agricultural production in the arid and semiarid region includes three broad types of agricultural practices: rangeland agriculture, dryland farming, and irrigation agriculture. Each has a different level of resource use and output (fig. 5). *Rangeland agriculture* occurs in areas where the native vegetation—predominantly grasses, grasslike plants, forbs,* and shrubs—are used commonly for grazing domestic livestock. Such areas are generally unsuitable for cultivation because they are too cool, too hot, too arid, or have soils too shallow or infertile to raise crops. *Dryland farming* is crop production through cultivation of the land. It relies on precipitation to supply plant-water needs. *Irrigation agriculture* supplements precipitation with additional water, primarily providing water for plant growth that is not normally supplied during the growing season.

The proportion of land used for each practice varies greatly across the Western States. Rangeland agriculture is the most land-extensive practice, followed by dryland farming and irrigation agriculture.

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*Herbaceous plants other than grasses.

Table 8.—Agricultural Services:[a] Number of Establishments,[b] Gross Receipts and Payroll, by State, 1978

State	Number of establishments	Gross receipts (in $000)	Annual payroll (in $000)
Great Plains:			
Texas	2,436	$ 281,493	$ 96,476
Nebraska	554	48,494	14,385
Oklahoma	562	36,447	8,821
Kansas	754	41,937	8,599
South Dakota	313	16,516	3,921
North Dakota	243	15,571	3,213
Mountain region:			
Arizona	441	104,250	41,705
Idaho	352	45,853	10,503
Colorado	355	31,981	8,477
Montana	238	13,528	2,971
New Mexico	118	8,741	2,686
Wyoming	79	4,197	1,394
Utah	98	5,905	1,120
Nevada	40	2,544	490
Pacific region:			
California	3,043	1,034,223	452,186
Washington	387	78,732	24,904
Oregon	331	31,197	8,943
17 Western States	10,344	1,801,609	690,794
United States	20,595	2,936,208	2,134,248

[a] Agricultural services consist of soil preparation services; crop services; veterinary services for cattle, hogs, sheep, goats, and poultry; animal services (except veterinary) for cattle, hogs, sheep, goats, and poultry; farm labor; and management services.
[b] Establishments having a dollar volume of business less than $2,500 are omitted.

SOURCE: U.S. Department of Commerce, Bureau of the Census, *1978 Census of Agriculture*, vol. 3, table 23, 1981.

Agricultural practices are dynamic. For example, an area can shift over a period of years from rangeland to dryland farming to irrigation. If irrigation water becomes limited and dryland agriculture is possible, a producer may choose to switch to crops that require less irrigation water, supply less than full water requirements to a crop, revert to dryland farming, or reseed an area and use it for grazing purposes. At the same time, a single farm or ranch can combine different types of agricultural practices. An individual can graze livestock on land not suited for cultivation but farm other areas where the soils are more fertile and where precipitation or irrigation water is sufficient for crop production.

The way agricultural practices change over time is evident in some of the Great Plains States. In 1944, about 2 million acres of land in Kansas, Oklahoma, Nebraska, and Texas were irrigated; by 1974 this total had grown to about 13 million acres (fig. 6). The shifts among agricultural practices continue. Irrigated acreage in the southern Great Plains (primarily Texas) decreased by over a half-million acres between 1974 and 1979 because of depletion of the Ogalalla aquifer and because of high-energy costs (11). As a second example, in the past 3 years, nearly 450,000 acres of grasslands in Colorado (approximately 700 square miles) that were previously used as range have been plowed in preparation for dryland farming (1). Another 700,000 acres of grasslands in South Dakota (approximately 100 square miles) have been plowed in the last 9 years (9). This trend has alarmed Federal and State officials who fear that this land is too fragile for intensive cultivation* and that the "Dust Bowl" days of the 1930's will return if irrigation water is in short supply or if a lengthy period of dry weather occurs.

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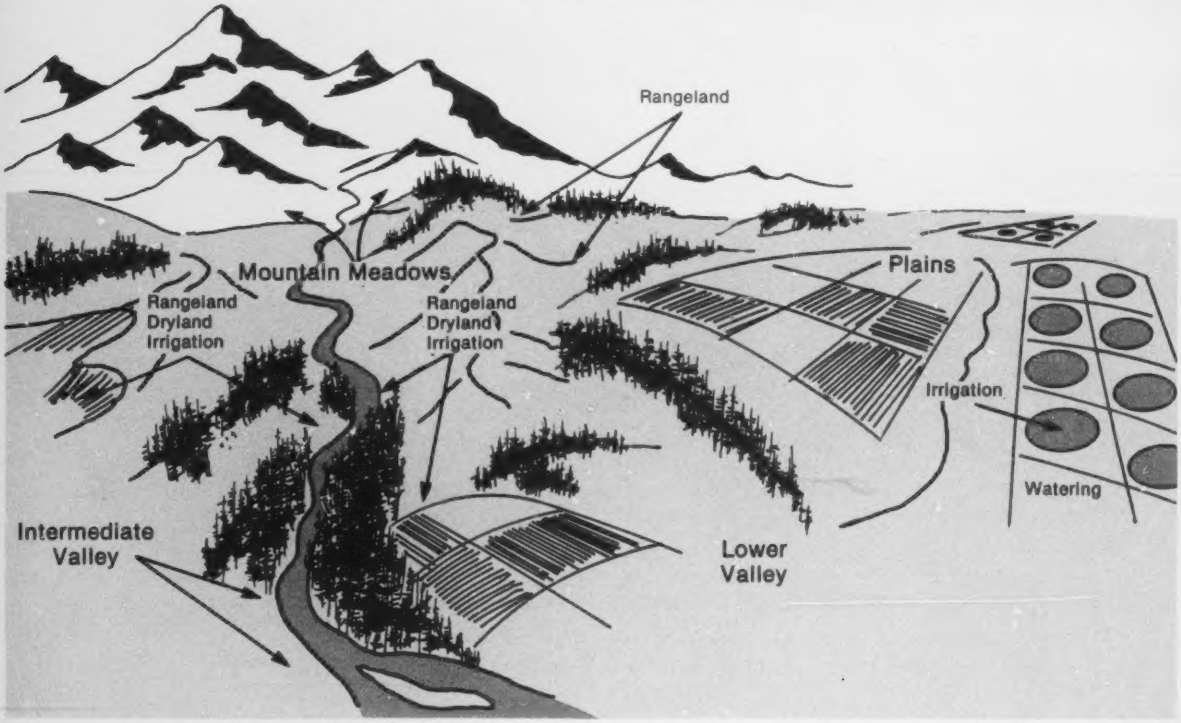
*Legislation has been introduced in Congress and in some States with the intent of curbing this practice. See also ch. XII.

Figure 5.—Schematic of Western Agriculture



SOURCE: U.S. Departments of the Interior and Agriculture, Environmental Protection Agency, Irrigation Water Use and Management, Interagency Task Force Report (Washington, D.C.: U.S. Government Printing Office, 1979), p. 34.

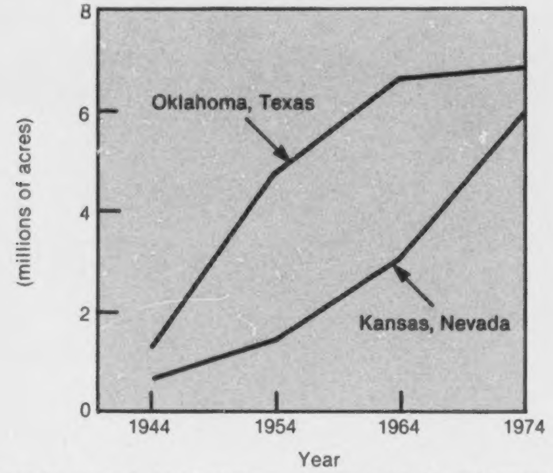
Rangeland Agriculture

After the Western territories were acquired by the Federal Government in the 1800's, much of the land was in the public domain. One value that became apparent to early inhabitants was its use for breeding and feeding domestic livestock, mainly sheep and cattle. Gradually, the livestock industry advanced throughout the Western region to supply settlers' needs and to fulfill the demand from Eastern States.

Rangeland is often classified by vegetation type: grassland or prairie types, desert shrub, chaparral, and understory herbage in both coniferous and hardwood forests (fig. 7). The natural productivity of a particular site varies greatly throughout the region and depends on precipitation, soils, and management.

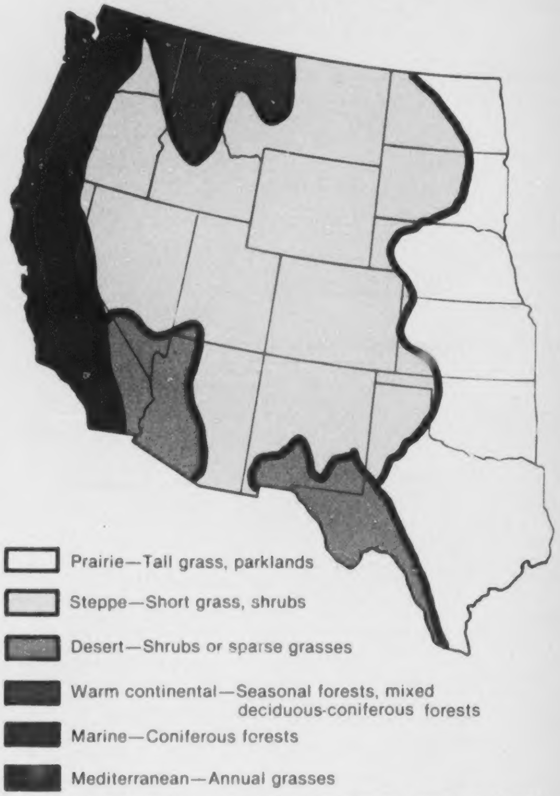
In general, rangeland agricultural areas produce forage for livestock. In addition, many of these areas are located in mountainous regions where surface runoff provides water to streams and rivers. Rangelands serve, too, along with forests, as the most productive and largest habitat for wildlife in the United States because they are managed less intensively than are other types of ecosystems. Federally owned rangelands are mandated to be managed for

Figure 6.—Irrigation Development in the Central and Southern Great Plains, 1944-74



SOURCE: Marvin E. Jensen, "Overview—Irrigation in U.S. Arid and Semiarid Lands, Office of Technology Assessment, unpublished draft report, 1982.

Figure 7.—Vegetation Types in the Arid and Semiarid Regions of the United States


Prairie—Tall grass, parklands
Steppe—Short grass, shrubs
Desert—Shrubs or sparse grasses
Warm continental—Seasonal forests, mixed deciduous-coniferous forests
Marine—Coniferous forests
Mediterranean—Annual grasses

SOURCE: R. G. Bailey, *Description of the Ecoregions of the United States*, USDA, miscellaneous publication no. 1391, 1980.

multiple products—grazing, timber, mining, water, and recreation.

Dryland Farming

The United States contains an estimated 350 million acres (546,000 square miles) of semiarid land (2). This area encompasses the Great Plains, eastern Oregon, eastern Washington, northern and southern Idaho, parts of western Colorado, Utah, and parts of the California Valley. Some of this land is suitable for crop production, especially using dryland methods.

In dryland farming, crops must be able to grow and produce under conditions of low precipitation. The number of crops currently adapted is limited. Wheat and barley, sorghum, millets, seed legumes (e.g., dry beans, dry peas, and lentils), safflowers, and sunflowers are produced commonly. The choice of a crop is further limited because some crops are adapted narrowly to certain climatic conditions (e.g., seasonal distribution of precipitation, winter and summer temperatures, and length of growing season).

The most extensive dryland crop area in the semiarid region of the United States is planted in wheat, which provides the highest cash income of all dryland crops. The major producing areas include the Great Plains, eastern Oregon, eastern Washington, and Idaho. Depending on climatic characteristics, different classes of wheat (i.e., hard red winter, hard red spring, durum, or soft white wheat) are grown in certain areas.

Barley can be grown in many areas where wheat is produced but tends to be less tolerant of cold weather. Much of the dryland region in California produces barley, and the crop is used for animal feed or malt.

Where wheat and barley production is limited by low precipitation or hot temperatures, farmers can grow sorghum, millets, and seed legumes. Grain sorghum is especially suited to parts of the southern and central Great Plains, where growing seasons are long. It can be used for animal feed or grazed by livestock. Other crops such as pinto beans, dry peas, lentils, safflowers, and sunflowers are locally important. For example, dry peas are grown in the Pacific Northwest and sunflowers are produced in North Dakota and western Nebraska.

Irrigation Agriculture

Irrigation agriculture accounts for roughly 50 million acres of agricultural land in the 17 Western States, or about 6 percent of the total agricultural land in the region (table 9). California is the leading State in number of acres irrigated, followed by Texas, Nebraska, Idaho, and Colorado. In 1978 more than 80 percent of the harvested cropland in Nevada, Arizona, and California was irrigated; from 50 to 80 percent of the harvested cropland in Idaho, Wyoming, and Utah was irrigated.

Irrigation can have several purposes. Its primary aim is to supply water to plants so that yields are not limited by insufficient water. Other purposes include:

- flushing soluble salts out of the soil, thereby preventing their harmful effects on plants;
- preventing severe freeze or frost damage to orchards, citrus nurseries, strawberries, ferns, and subtropical fruits;
- seed-bed preparation;
- waste treatment of effluents from food processing industries and municipal sewage facilities;
- reducing heat stress in plants by wetting the foliage; and
- facilitating harvest of root crops (e.g., sugar beets, potatoes) (6).

Irrigation is an economically important practice in the arid and semiarid region because it allows crop production where it might not otherwise be possible. Furthermore, with its value in controlling soil water and in reducing the risk associated with crop production,

Table 9.—Nonirrigated and Irrigated Cropland,[a] 17 Western States, 1977

State	Nonirrigated (000 acres)	All cropland irrigated (000 acres)	Percent of total cropland irrigated
Great Plains:			
North Dakota	26,835	78	<1
Kansas	25,631	3,175	11
Texas	22,510	7,929	26
South Dakota	17,684	472	3
Nebraska	13,794	6,905	33
Oklahoma	11,073	710	6
Mountain region:			
Montana	13,294	2,061	13
Colorado	7,699	3,394	31
Idaho	2,743	3,547	56
Wyoming	1,320	1,650	56
New Mexico	1,203	1,079	47
Utah	655	1,160	64
Arizona	145	1,167	89
Nevada	4	1,103	100
Pacific region:			
Washington	6,179	1,772	22
Oregon	3,139	2,009	39
California	1,920	8,153	81
Total, 17 Western States	155,828	46,364	23
Total 48 States	357,027	55,594	13

[a] Cropland includes cultivated cropland, pasture, hay land, orchards, and vineyards.

SOURCE: U.S. Department of Agriculture, Soil Conservation Service, *1977 National Resources Inventory, Basic Statistics*, revised February 1980, table 3.

Box C.—Rainfall and the Western Settler

One element that strongly shaped agriculture in the Western States was the environment, particularly limited precipitation. Explorers to the region in the early 1800's noted that the West was unsuited for farming operations and called it "A Great American Desert." Some individuals who later attempted to farm without irrigation affirmed this notion—the weather was unpredictable; precipitation was often erratic, scant, and poorly distributed; and temperatures were extreme.

Despite the crop failures sustained by many farmers and the powerful presence of the cattle industry, hopes for a more intensive type of agriculture than ranching remained alive. Some colorful myths developed that promised rain to the farmers:

- rain would follow the plow because evaporation would increase from worked soil,
- rain would follow the train because raindrops would form around smoke particles,
- rain would follow the telegraph because of electricity in the air,
- rain would follow a military battle (experiments were even conducted in Texas with explosives and cannons—without success), and
- rain would follow settlement because the people were good and worthy with a destiny to fulfill.

Farming practices in the West strongly reflect this past experience. Dryland farming techniques eventually evolved that conserved precipitation during the winter months for use during the growing season. Crops were selected that did well despite the low amounts of water. Water supplies were developed (by reservoir and canal construction) to enable crop production in areas that would have little potential for farming otherwise.

farmers who irrigate generally have higher and more stable yields than do dryland farmers.* Moreover, such producers have a wider choice of crops.** These crops include corn, cotton, wheat, sorghum, high-value specialty crops such as fruits, nuts, berries, vegetables, sweet corn, and melons, and field seed crops (table 10).

Structure of Western Agriculture

Farm Size and Ownership

Many factors influence farm/ranch size and ownership patterns including natural resources, availability of capital, export demand for crops, availability of nonfarm employment, commodity programs, credit availability, and tax rules.*** In the Western States, farms and ranches tend to be larger than in the rest of the United States; dryland farms and ranches tend to be larger than irrigated areas.

For purposes of this discussion, the farming regions are as follows:

1. the Great Plains include North and South Dakota, Nebraska, Kansas, Oklahoma, Texas, Colorado, Wyoming, and Montana;
2. the Southwest includes California, Nevada, Utah, Arizona, and New Mexico; and
3. the Northwest includes Washington, Idaho, and Oregon.

Among the Western States, as in the rest of the United States, there has been a trend toward fewer but larger farms. In the Great Plains in 1978, the average farm size was about 900 acres (over two times the national average of 415 acres). Cash receipts per farm were about $55,000 (the national average was about $44,000). Most of the farms in the region were less than 500 acres in size, but about one-fifth (about 100,000 farms) were over 1,000 acres. Over one-half of the farms were owned by an individual or family; many operators also rented land.

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*Frederick and Hanson (5) compared yields among western dryland and irrigated crops of corn, sorghum wheat, and cotton to the East. Irrigated crops had significantly higher yields per acre than either dryland crops or crops grown in the East. For example, with irrigation, average yields for corn increased from 48 to 115 bushels per acre. In the East, average yields were 89 bushels per acre.

**The wide selection of crops available to irrigators is reflected in the fact that in California, over 200 commercial crops are grown.

***This discussion is largely from Schertz, et al. (10).

Table 10.—Irrigated Acreage of Selected Crops, 17 Western States, 1978

Crop	Acres harvested (000 acres)	Acres irrigated (000 acres)	Percent of crop irrigated
Hay crops	29,116	8,954	31
Corn	13,870	7,850	57
Cotton	9,260	4,555	49
Wheat	46,811	2,987	6
Orchard crops	2,635	2,306	87
Sorghum	11,620	2,019	17
Barley	7,512	1,964	26
All vegetables harvested for sale	1,647	1,445	88
Irish potatoes	867	716	83
Field seed crops	905	303	33
Oats	4,487	223	5
Strawberries	21	18	86

SOURCE: U.S. Department of Commerce, Bureau of the Census, *1978 Census of Agriculture*, vol. 4, ch. 1, tables 9-13, 1981.

Farm size in the Southwest, as measured by resources controlled and output per farm, far exceeds the U.S. average. In 1978, average farm size was 1,300 acres and cash receipts per farm totaled about $130,000. Looking only at crop production, the value of crops sold per farm in the Southwest was 3½ times the U.S. average. Also of interest was the distribution of farms and sales among size classes. In 1974 the Southwest had a slightly higher proportion of small farms (less than 180 acres) than did the rest of the United States (reflecting specialty-crop production); however, more than 55 percent of Southwestern farms exceeded 1,000 acres, compared with 34 percent for the United States. Three percent of all farms had more than $500,000 in annual sales and produced 60 percent of the cash receipts from farming.

Corporate farms (both family held and nonfamily owned) are another important feature of the Southwest. In 1978 corporate farms controlled nearly 20 percent of Southwestern farmland. Their role varies with crop and area. For example, in the southern San Joaquin Valley of California, conglomerates operate some large producing-processing-marketing farms. These farms produce a large variety of crops, including tree fruits, nuts, and vegetables.

Characteristics of Northwestern farm production are difficult to assess because of the diverse crop-production capabilities in the region. In 1978 average farm size was slightly over 500 acres; however, farm size tended to be much lower along the coastal areas than in the intermountain irrigated area or dryland farming region east of the Cascade Mountains. Average farm sales were approximately $75,000. A majority of farms were owned by an individual or family.

Role of Labor

Since World War II, one of the most dramatic shifts in agriculture has been the substitution of capital goods (e.g., tractors and other farm machinery, farm chemicals, and irrigation water) for labor. On the Great Plains, for example, fewer farms and the development of larger tractors and other machinery have reduced farm labor requirements and the number of farmworkers. Over the period from 1960 to 1977, the number of farmworkers declined from 1.25 million to 785,000. About one-fourth of these workers were hired; the rest of the labor force consisted of family farm labor.

Where high-value specialty crops are grown, considerably more hired labor is used. For example, in the Southwest in 1977, the bill for hired labor totaled $1.9 billion, 26 percent of the U.S. hired labor charge. Of the total farm work force in the region, 69 percent was hired labor, compared with 31 percent owner and family labor. Comparable national totals were reversed.

Much has been written about the hired labor force in the Southwest. In general, it is characterized by its impermanence—80 to 90 percent of hired labor work less than 150 days. Furthermore, of all the occupational classes in the United States, farm laborers are the least educated. Male farm laborers between the ages of 25 and 44 have an average of 9 years of schooling (4). Many are minorities, and these workers may find little alternative employment outside of agriculture.

TRENDS

The long-term future of Western agriculture is uncertain. The elements that have shaped its past—natural resources, people, science and technology, economics, and Government policies—will invariably affect its future. New considerations, unknown or discounted as unimportant at present, may influence the future direction of Western agriculture. Examples of these elements include climatic change, increased foreign and corporate ownership of farmland, energy shortages, increased water restrictions on agriculture, resource degradation, world food shortages or famine, widespread crop failure (domestically or internationally), international conflicts, or other crises.

Irrigation agriculture raises particular concern at present. The West supplies the Nation with important foodcrops, especially perishables, and most of these crops are irrigated.* Furthermore, mild winter temperatures and fertile soils give some areas of the region (e.g., California and Arizona) a virtual monopoly in producing numerous specialty crops (e.g., almonds, walnuts, and wine grapes). However, large tracts of land produce corn, sorghum, alfalfa, wheat, and lesser grains that are produced in abundance elsewhere.** In recent years, some of these commodities have been in surplus. Moreover, decisionmakers at all levels of government are concerned that the water-short West may not be able to sustain current levels of population growth, accommodate new energy and industrial development, and maintain its irrigated acreage (see discussion of completing uses in ch. V). Individuals and groups that support environmental conservation worry also about the effects of irrigation on land, surface flows, and wildlife. Depletion of ground water resources, especially in the southern Great Plains, threatens not only the well-being of agricultural producers who use this water but also rural communities that are agriculturally based. Furthermore, current use of easily tapped ground water diminishes the possibility of using this resource in the future. Added together, these factors lead many analysts to believe that irrigation in its present form will not continue to make the contributions to agricultural growth that it has in the past (5,8).

The social ramifications of irrigation are less well understood and more difficult to assess, but important questions nonetheless. Irrigation agriculture often affects farm size and ownership dramatically—changing land use patterns, increasing land values, and limiting ownership to large farmers and ranchers, outside investors, or corporations that can more easily afford the high risks and high investments irrigation often necessitates (7). Reliance on migrant farm labor, especially in fruit and vegetable crop production in the Northwest and Southwest, raises questions about income equity, housing standards for migrant workers, and immigration policies (12).

A second set of issues affects agricultural land and its competition with nonagricultural uses: urban development, recreation, and transportation. Estimates indicate that from 1967 to 1977, some 2 million to 3 million acres of agricultural land (cropland, pasture, range-

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*For example, the U.S. Department of Commerce reports that from 1973 to 1977, the 17 Western States supplied 55 percent of fresh fruits and vegetables to 36 major U.S. cities (4).

**Many of these crops are fed to cattle and their increased availability has been one of the most obvious factors in the growth of the feedlot industry in Nebraska, western Kansas, eastern Colorado, and the panhandles of Texas and Oklahoma during the last 25 years.

Box D.—Reducing Agricultural Surpluses

During the 1981 and 1982 crop years, U.S. and world grain production reached record levels. Favorable weather contributed to this increase. At the same time, the demand for U.S. agricultural products slowed, and domestic grain stocks ranged to new highs mainly caused by weak economic conditions in the United States and in other parts of the world, financial instability in several countries, a strong U.S. dollar, market losses related to the Soviet embargo, continued East-West tensions, and restrictive marketing practices in some foreign markets. For farmers in this country, the high grain stocks meant reduced crop prices; in calendar 1982, average domestic prices for wheat and coarse grains dropped to their lowest levels since 1979.

Following these events, the administration launched several programs to reduce stock, lower Federal commodity payments, and bolster prices. In 1982, USDA offered farmers an acreage-reduction program in an effort to curb production. Under this program, farmers voluntarily agreed to reduce the number of acres they would plant in a particular crop (e.g., corn, wheat, cotton) by a specified percentage. In return, they became eligible for Federal price support benefits. However, good weather and the late program announcement negated its intended effects.

For 1983, the program was expanded to include paid diversion (i.e., farmers who comply with the voluntary acreage reduction may further reduce their acreage and receive cash payments), an expanded export credit program, and a payment-in-kind (PIK) program. The novel PIK program attracted much interest from the public. Under this program, farmers who removed from production additional acres over what they agreed to take out under current acreage-reduction programs received as payment a certain amount of the commodity they would have grown on these acres. The commodity then became the property of the individual and could be disposed of in any way the farmer wished. Crops of wheat, corn, grain sorghum, cotton, and rice were included in PIK.

Secretary Block, in detailing features of the program, noted, "We have a threefold objective with PIK—reduce production, reduce surplus stockholdings, and avoid increased budget outlays that would otherwise be necessary under price support programs." Furthermore, he stated, "It is unlikely our surplus will be substantially reduced any time soon by increased exports. PIK is aimed at bringing supply more in line with demand."

SOURCES: USDA, *Payment In Kind Fact Sheet*, 1983. Remarks Secretary John R. Block, Jan. 11, 1983. Economic Research Service, *World Agriculture Outlook and Situation*, WAS-31, March 1983.

land, and forest) were converted each year to nonagricultural uses (3). About one-third was in active use. Two points become evident. First, with current low prices of many farm commodities (particularly grains and cotton), many farmers are facing financial ruin. Some Western farmers may leave agriculture, thereby easing the way for additional land conversion, which may ultimately affect the Nation's capacity to produce food and fiber. Second, expansion of urban areas often occurs at the expense of local agricultural land. Farmers may decide to retire from agriculture or move their operations to other lands, which may be less productive and more erosive, and which may entail higher production costs.

A third but related set of issues affects agricultural practices in the region. Will the shift from rangeland agriculture to dryland farming or irrigation on privately owned lands create another "Dust Bowl"? If these areas are converted but later abandoned, how can they be rehabilitated and made productive again, and who should bear the costs of reclamation?

New technologies and Government policies (including water, food, export, and agricultural research policies) may drastically shape tomorrow's agriculture in the arid and semiarid region. Traditional agricultural practices may change. Irrigation, as it is practiced today, may become less important; producers may move away from reliance on a single crop for their income toward multiple-use of croplands and rangelands. Some native plants and animals may be used more intensively for food, fiber, energy, and industrial feedstocks. Greenhouses and fish enclosures may gradually become more common, capturing the incoming solar radiation and highly concentrating food production over small areas of land.

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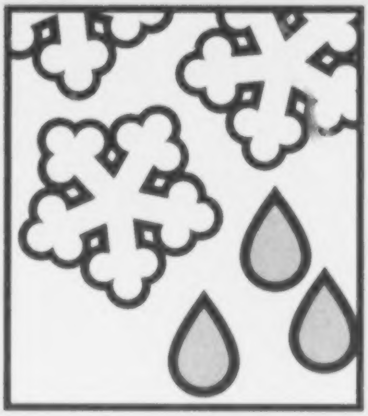

Water Supply and Use in the Western United States

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Chapter III

Water Supply and Use in the Western United States

The existing relationship between water supply and use in the Western United States determines both the extent of the supply/use problem and the potential of any individual technology to alleviate current or anticipated problems. Regional water-use patterns, that have evolved as a result of the spatial and temporal variability of water supplies, are linked in a complex fashion by the hydrologic cycle. The understanding of the hydrologic cycle and of current or potential water problems is inextricably tied to the way in which relevant data are collected and analyzed.

This chapter provides an overview of the existing water resources and current water uses in the Western United States. It is the foundation for assessing water-related technologies in succeeding chapters. The purpose of this chapter is: 1) to outline the major components of the hydrologic cycle, their interrelationships, and their variability as they are altered naturally or technologically; 2) to discuss the adequacy of data available on the quantities of water in various components of the cycle and problems of water-data acquisition and analysis; and 3) to evaluate, in the context of available data, the nature of the supply and demand relationships of the major river systems of the Western United States. The chapter begins with a review of the major Federal agencies dealing with water.

SURVEY OF FEDERAL AGENCIES INVOLVED IN WATER

Various agencies within the Federal Government have been involved in water and water-resources management since the United States was formed. Generally, these activities have been oriented toward supporting the specific mission and program of each agency.

Discontinued Federal Efforts

Water Resources Council: Established by the Water Resources Planning Act of 1965 (Public Law 89-90); produced a first National Water Assessment in 1968, based mainly on data compiled and analyzed by major Federal agencies; produced second National Water Assessment in 1978 which updated information on the Nation's water resources and which attempted to determine the adequacy of water supplies for future use; agency functions essentially abolished in 1981 with termination of funding.

National Water Commission: Established by Act of Congress (Public Law 90-515) for a fixed term; produced in 1973 a report to the President, *Water Policies for the Future,* that considered the Nation's water-resource supplies and uses and outlined several alternative futures and possible actions for water-resource development to the year 2020; Commission terminated with production of report.

Office of Water Research and Technology: Established within the Department of the Interior; sponsored State programs of research, development, and demonstration in the fields of water and water-related resources generally through State water research institutes; abolished by Reagan administration in early 1980's.

Ongoing Federal Efforts

Currently, Federal responsibility for water-data acquisition, planning, and management of particular relevance to this assessment includes the Departments of Agriculture (USDA), Commerce (DOC), Defense (DOD), and Interior

(DOI) and the Environmental Protection Agency (EPA). The key mission and water-related activities of the principal agencies within each Department are summarized below from *Plans for Water Data Acquisition by Federal Agencies Through Fiscal Year 1983* (11).

Agricultural Research Service (USDA): Conducts research on water-use technologies for agriculture, analyzes data on agricultural water use, and develops practices involving use of soil, water, and air resources for agriculture.

Forest Service (USDA): Maintains responsibility for water resources that are derived from Forest Service lands, protects tributary waters, and conducts water-resource research relevant to the long-term productivity of forests and rangelands.

Soil Conservation Service (USDA): Collects water-related data, including snow data, for downstream agricultural users and undertakes soil, water, and related resource projects with farmers, ranchers, and groups of individuals to improve production and protect the resource base.

National Oceanic and Atmospheric Administration (DOC): Includes the National Weather Service; provides water data in support of basic hydrographic surveys, research, water regulations, specialized users, and safe navigation; conducts some weather modification work.

U.S. Army Corps of Engineers (DOD): Plans, designs, constructs, and operates water-resource projects throughout the United States; performs similar analyses for nonstructural projects.

Bureau of Land Management (DOI): Manages water resources on the public lands administered by the Bureau and conducts inventories and analyses of quality and quantity of surface- and ground-water resources on public lands.

Bureau of Reclamation (DOI): Plans and constructs water projects in the 17 Western States to provide flood control, water for irrigated agriculture, municipal and industrial water supplies, and hydroelectric generation; involved in some weather modification work.

Fish and Wildlife Service (DOI): Responsible for overseeing national interests in the conservation of fish and wildlife and their habitat; provides ecological expertise to water-resource planning, development, and management activities.

U.S. Geological Survey (DOI): Collects and analyzes water data, operates the National Water Data Exchange (NAWDEX) program, and provides hydrologic information for the use and management of the Nation's water resources.

U.S. Environmental Protection Agency: Conducts research and demonstration projects on water quality, monitors water quality, establishes and enforces water-quality standards, and defines water pollution controls.

WATER SUPPLY: THE HYDROLOGIC CYCLE

Present agricultural practices in the arid and semiarid regions of the Western United States are the result of complex interactions involving both the biophysical environment and human modification of and adaptation to that environment. Water is one of the primary limiting factors in this environment, and it is generally only where this limitation has been overcome by rangeland, dryland, and irrigation technologies that agricultural production has been feasible.

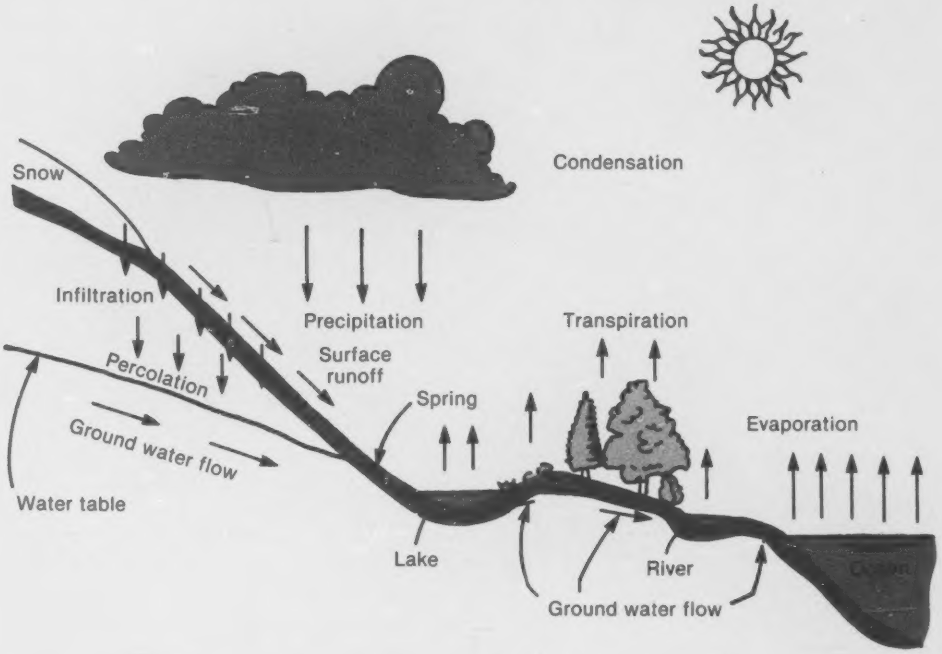
In arid and semiarid areas, both temporal and spatial inequities in the distribution of water lead to shortages. These shortages may be chronic for certain areas, such as the deserts of the Southwest, or seasonal in areas that derive the bulk of their water supply from the annual spring snowmelt and runoff. Water-related problems are site-specific to some extent. This geographical aspect of the problem varies with agricultural practices and depends, to some extent, on which water processes are involved.

The fundamental, unifying concept in the study and understanding of water is the hydrologic cycle (fig. 8). The cycle is the conceptual model that relates the interdependence and continuous movement of all forms of water through the vapor, liquid, and solid phases. It may be considered the central concept in hydrology.

The components of the hydrologic cycle are:

- *Precipitation:* Water added to the surface of the Earth from the atmosphere. It may be either liquid (e.g., rain and dew) or solid (e.g., snow, frost, and hail).
- *Evaporation:* The process by which a liquid is changed into a gas. In the context of the hydrologic cycle, the most important form of evaporation is probably that

Figure 8.—The Hydrologic Cycle


Condensation
Snow
Infiltration
Precipitation
Transpiration
Surface runoff
Percolation
Spring
Evaporation
Ground water flow
Water table
Lake
River
Ocean
Ground water flow

Water passes continuously through this cycle from evaporation from the oceans into the atmosphere through precipitation onto the continents and eventual runoff into the oceans. Human use of water may modify this cycle at virtually every point.

SOURCE: H. Hengeveld and C. DeVocht, *Urban Ecology* 6(1-4):19, 1982.

which takes place from the seas and oceans. This is the main source of water on land areas.

- *Transpiration:* The process by which water vapor passes through a living plant and enters the atmosphere.
- *Infiltration:* The process whereby water soaks into, or is absorbed by the surface soil layers.
- *Percolation:* The downward flow of water through soil and permeable rock formations to the water table.
- *Runoff:* The portion of precipitation that comprises the gravity movement of water in surface channels or depressions. It is a residual quantity, representing the excess of precipitation over evapotranspiration when allowance is made for storage on and beneath the ground surface.

All water is involved in continuous cyclical movement according to the hydrologic cycle. Some of the water vapor in the atmosphere gives rise to precipitation through complex processes of condensation and freezing. Not all precipitation reaches the surface of the Earth. Some evaporates while falling and, more importantly, some is intercepted by vegetation or artificial structures and is then returned to the atmosphere by subsequent evaporation.

The watershed, or river basin, is the fundamental geographic unit of hydrology. It is also the fundamental biophysical unit within which technologies to affect precipitation and runoff must be assessed. A watershed is a land area surrounded at its perimeter by highlands that cause precipitation falling within the watershed's bounds to flow generally toward its center to form rivers or streams. In 1970, the U.S. Water Resources Council divided the United States into geographic units based on the watershed, or river basin, for the collection and organization of hydrologic data (12) (fig. 9).

Water reaching the surface of the watershed follows one of three courses. First, it may remain on the surface as pools and surface moisture that eventually evaporates back into the atmosphere. Or it may be stored on the surface in the form of snow until air temperatures are high enough to allow melting and runoff. Storage as snow is a common occurrence during at least a portion of each year in much of the Western United States.

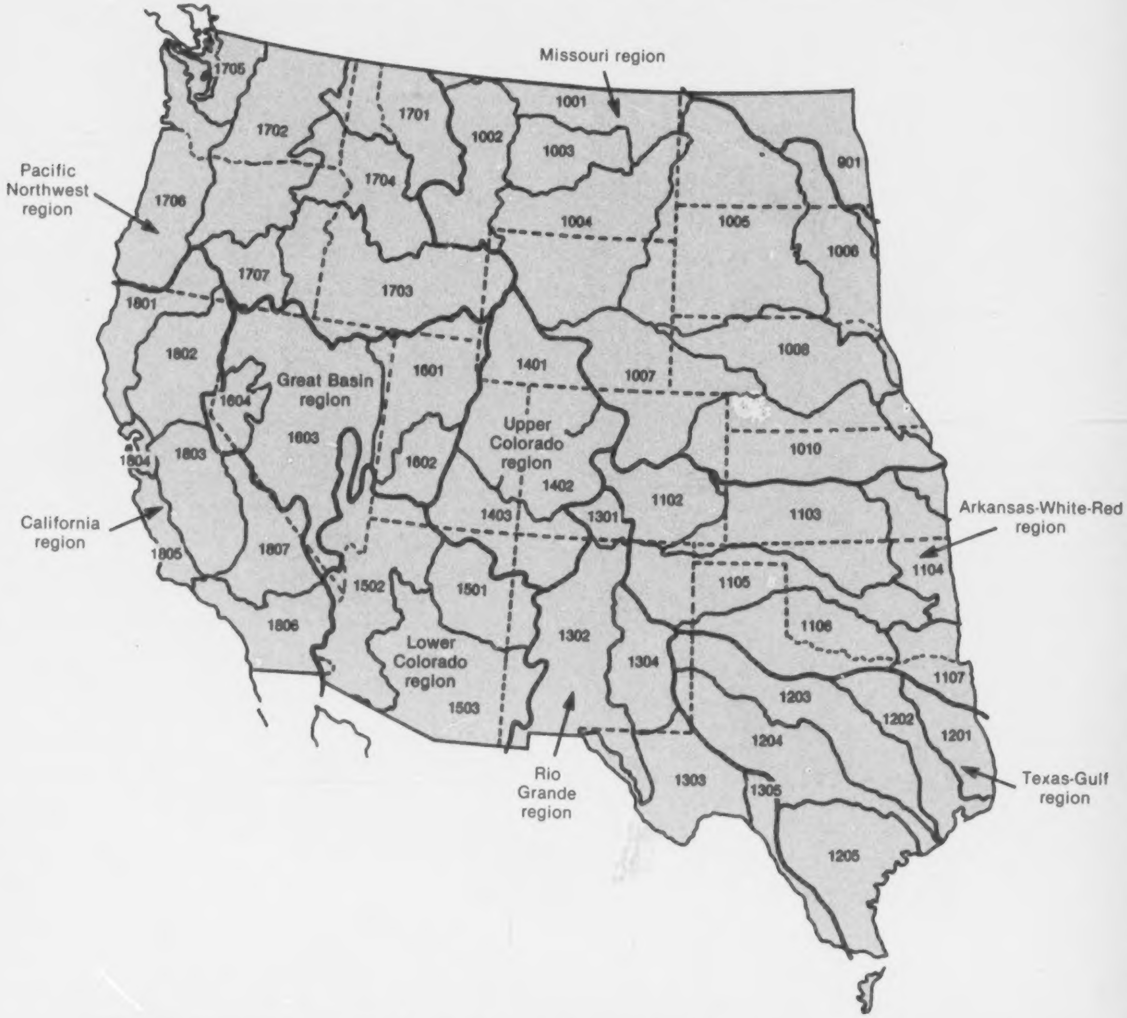
Second, precipitation reaching the ground may flow over the surface into depressions and channels to become surface runoff in the form of streams and lakes. It then moves by evaporation back into the atmosphere, or by infiltration into the soil and toward the ground water table, or by continued surface flow back into the seas.

Third, falling precipitation may infiltrate the surface and percolate to ground water. As ground water, it is stored for periods ranging from days to thousands of years. Ground water can be removed naturally by upward capillary movement to the soil surface and plant root zone, by ground water seepage, or by runout into surface streams, lakes, and oceans. Some of it is removed by pumping from wells, in which case it again arrives at the surface as artificial precipitation and follows one of the paths described above.

Generally acceptable estimates of the amounts of water passing annually through the various phases of the hydrologic cycle for the Western United States have not been found in the literature. Based on estimates for the United States as a whole, however, more than 1,500 million acre-ft of water are added to the Western United States each year as precipitation and the majority of this is consumed by evapotranspiration (12). Approximately 500 million acre-ft constitute the measured streamflow from the region (e.g., 4,12) and 50 million acre-ft of water are added annually to the ground water reserves of the region.

Runoff is not uniformly distributed throughout the Western United States. Streamflow to the Pacific Ocean, primarily from the Pacific Northwest region, is estimated to be over 335 million acre-ft annually, or nearly 70 percent of the total for the entire region. Almost all of the remaining surface runoff flows into the Mississippi River and ultimately into the Gulf of Mexico. In general, those areas with the low-

Figure 9.—The Water Resources Regions of the Western United States


Missouri region
1705
1702
1701
1002
1001
1003
901
Pacific Northwest region
1706
1704
1004
1005
1006
1707
1703
1801
1802
1601
1401
1007
1008
Great Basin region
1604
1603
Upper Colorado region
1010
1804
1803
1602
1402
1102
1103
California region
1403
1301
Arkansas-White-Red region
1805
1807
1104
1105
1502
1501
1106
1806
1302
1304
Lower Colorado region
1107
1503
1203
1202
1201
1204
Rio Grande region
1303
1305
Texas-Gulf region
1205

The conterminous portion of the Western United States has been subdivided into 9 water resource regions, containing 52 subregions as defined by the Water Resources Council (WRC) for the Second National Water Assessment. These are shown below. The water resource regions in the Western United States: (10) the Missouri region, (11) the Arkansas-White-Red region, (12) the Texas-Gulf region, (13) the Rio Grande region, (14) the Upper Colorado region, (15) the Lower Colorado region, (16) the Great Basin region, (17) the Pacific Northwest region, and (18) the California region.

The water resources regions consist of either the drainage area of a major river, such as the Missouri region, or the combined drainage areas of a series of rivers, such as the Texas-Gulf region. The second level of classification, the subregion, consists either of an area drained by a river closed basin(s), or a group of streams forming a coastal drainage area. All subregion boundaries are hydrologic (i.e., are located along watershed boundaries) except where discontinued at international boundaries. The subregions were reorganized by WRC in 1974 and 1978. They do not correspond to those in use by the U.S. Geological Survey.

SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978).

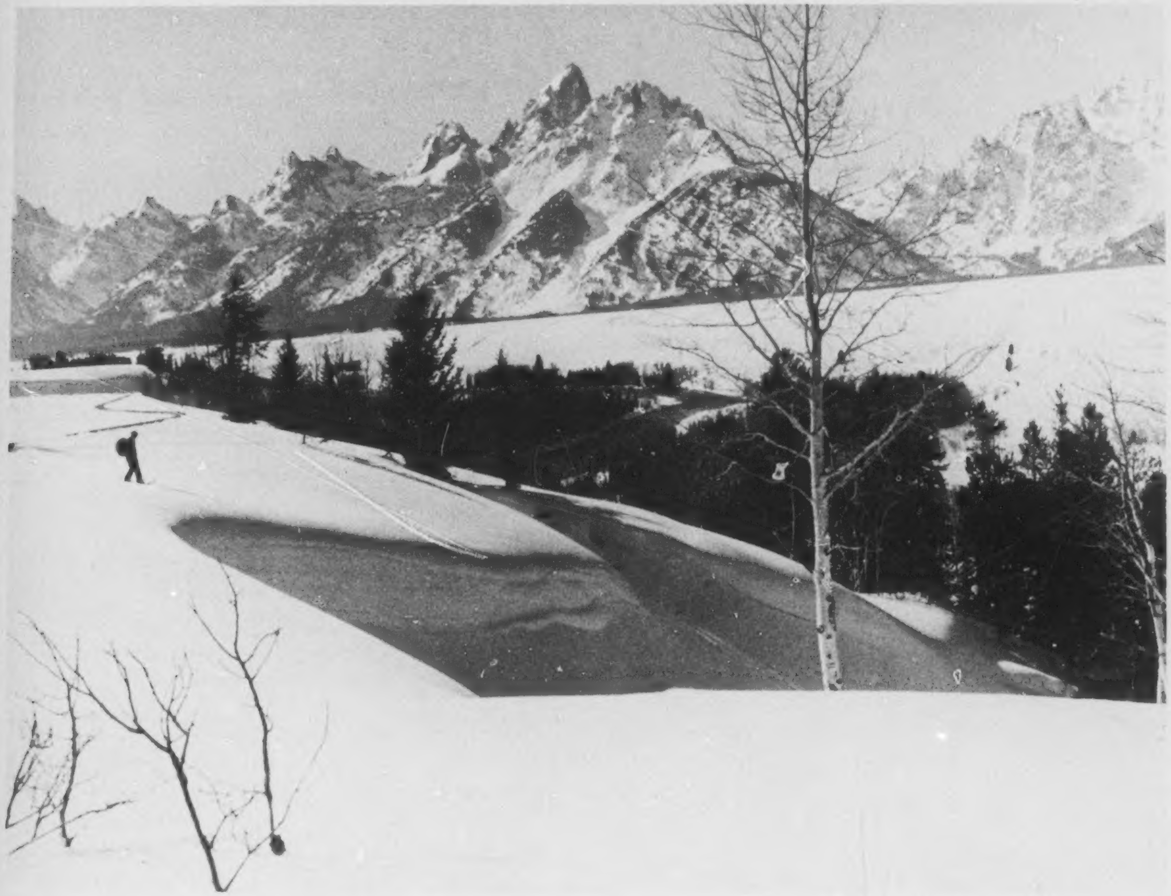


Photo credit: USDA Soil Conservation Service

The most important source of renewable surface water supplies in the Western United States is the mountain snowpack. This photograph of a snowpack in the Teton Range has an average depth of some 5 ft. When Western snowpacks melt in the spring and summer they supply an estimated 70 to 100 percent (depending on location) of the total annual surface runoff for all river basins except the Texas-Gulf region

est annual precipitation contribute runoff to rivers only during sporadic summer thunderstorms. The bulk of the runoff in the region originates from the melting mountain snowpack each spring and summer. Following snowmelt, runoff enters the river system of the region, where it is often stored in surface reservoirs until the period of peak demand in late summer.

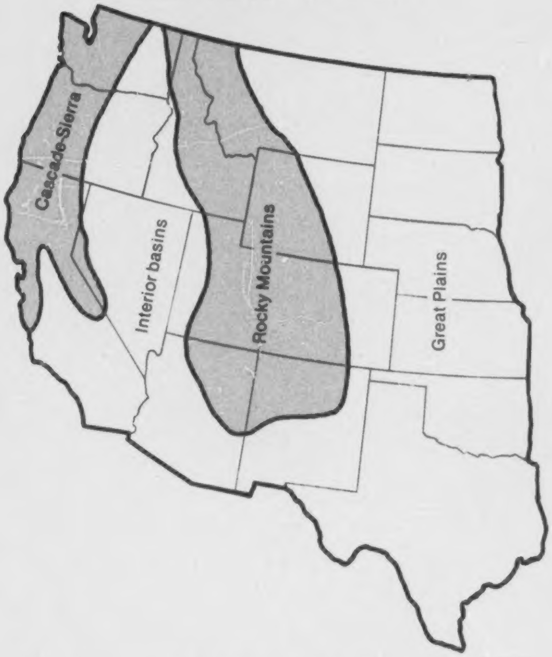
The Components

The Western United States has a wide range of hydrologic environments, both in terms of the absolute amount of water in the various hydrologic components and also in terms of the interrelationships among the components.

Precipitation

The primary factor determining the amount of precipitation that falls over the 17 Western States appears to be topography (fig. 10). The four broad north-south zones are generally more uniform within themselves than are any two adjacent east-west zones. These general hydrologic zones are: 1) the mountain ranges of the Pacific coast, consisting mainly of the Sierra and Cascade Mountain ranges; 2) the interior basins; 3) the Rocky Mountains; and fi-

Figure 10.—Major Landforms of the Western United States



The total amount of precipitation and the form in which it falls (snow or rain) are related more to the major landforms of the region—i.e., mountains or plains—than to any other factor.

SOURCE: Office of Technology Assessment.

nally 4) the Great Plains, which extend from the eastern side of the Rocky Mountains to the western edge of the more humid portions of the continent, at approximately the 100th meridian, or the Missouri River.

Air masses that carry atmospheric moisture over the region move generally onto the west coast of the continent and follow a west-to-east path. As these air masses cross the Western portion of the United States, they are forced upward to cross each of the two major mountain chains in their path. The forced, or orographic, rise produces a band of increased precipitation associated with each of the major mountain chains. The subsequent descent on the downwind sides of these chains produces the two belts of generally deficient rainfall.

Precipitation amounts in the region vary widely, depending largely on the geographical location of a particular site with respect to these mountain chains and on the location of the major storm tracks (fig. 11). The percentage of annual precipitation that falls as snow is highest in the mountain ranges (fig. 12). The snow/rain ratio is particularly important in understanding the role played by precipitation at a particular site. Snow represents a form of natural storage during months of generally low water demand and a natural release to surface runoff at a time approximately coincident with peak demand. Therefore, it is more important to agriculture than is an equivalent amount of rainfall received when demand is low or stored at high cost.

The greatest amount of precipitation in the Western United States occurs in the Pacific Northwest, on the Olympic Peninsula, and on the west slope of the Cascade Mountains where amounts total over 100 inches per year. At the opposite extreme, values of less than 5 inches per year are recorded in some of the southwestern deserts.

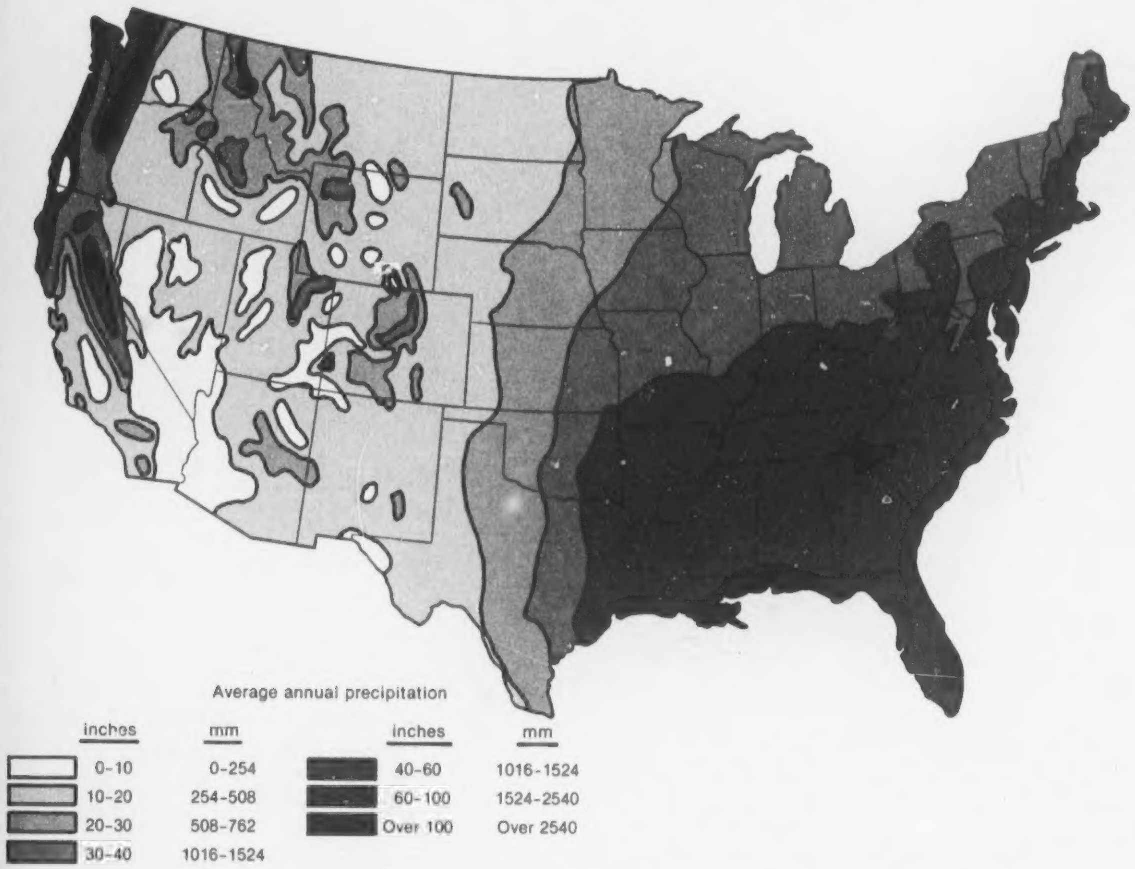
The annual regime of precipitation is highly variable from one part of the region to another. As much as half of the annual precipitation may fall during the growing season in much of the eastern portion. On the Pacific coast, the distribution is reversed, and virtually all of the total annual moisture falls during winter.

Evapotranspiration

Evaporation and transpiration are processes that return water to the atmosphere. These processes are controlled by the amount of energy available to convert liquid water to vapor and are limited also by the amount of available water. The term "evapotranspiration" is used to designate the loss of water from the soil by evaporation and from plants by transpiration.

Values of evapotranspiration are more difficult to evaluate than those of precipitation because in many areas of the West total evapo-

Figure 11.—Average Annual Precipitation of the United States



Precipitation patterns closely reflect a region's landforms, which are a primary factor in determining the amount of water available for use in any given area.

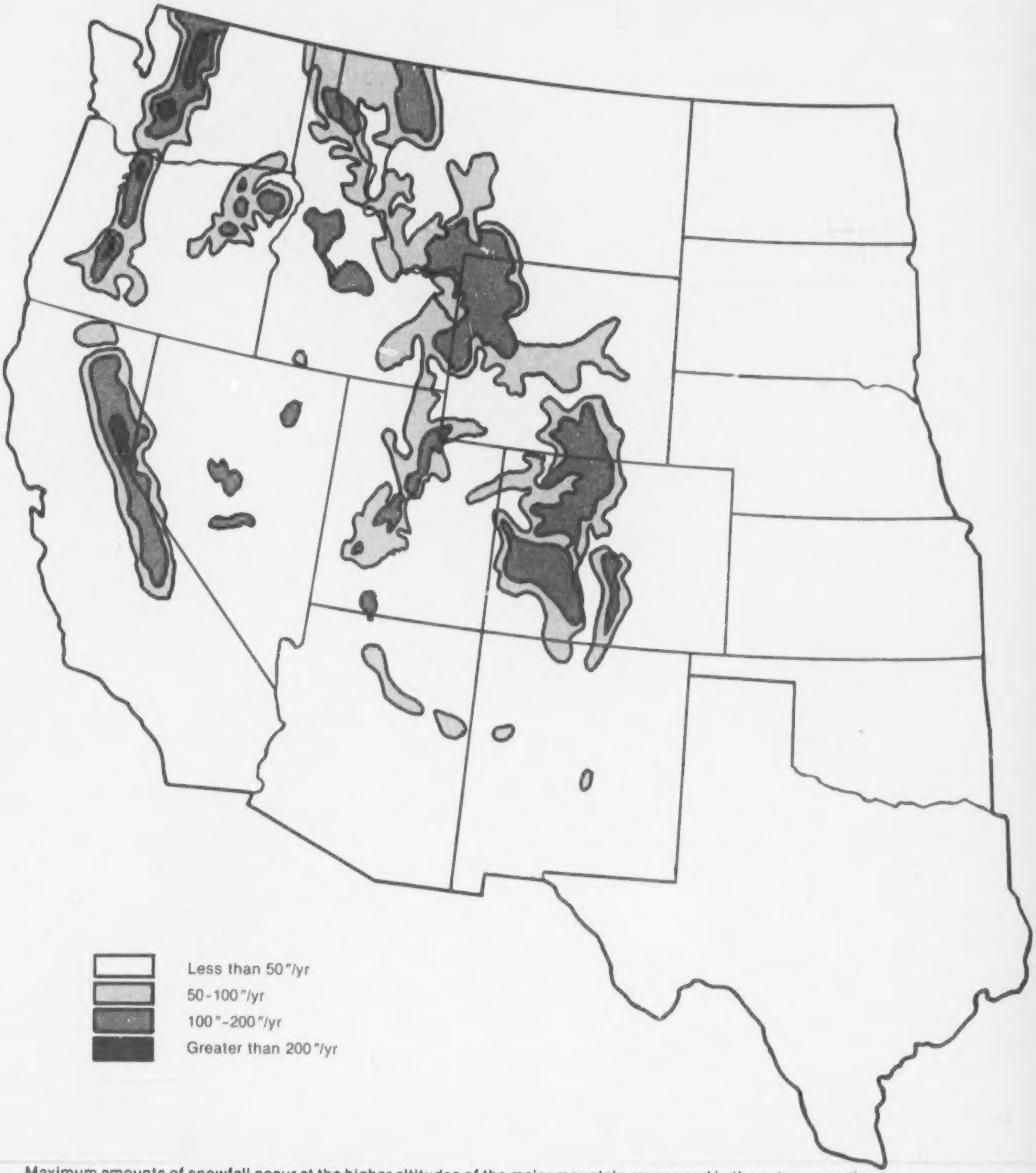
SOURCE: H. Anderson, M. Hoover, and K. Reinhart, *Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Suply*, USDA Forest Service General technical report PSW-18, 1976.

transpiration is limited only by the available water supply. Potential evapotranspiration is the amount of water that would be lost if precipitation were unlimited. Throughout the interior basins, the desert southwest, and much of the southern portion of the Great Plains, actual evapotranspiration is a small fraction of potential evapotranspiration.

Actual evapotranspiration is determined in part by the seasonal distribution of precipitation and in part by air temperature regimes. If precipitation occurs largely during winter, as is the case in the mountain ranges of the Western United States and along the Pacific coast, much of this precipitation runs off or infiltrates the soil. For most of the region, however, precipitation occurs during the summer, when evapotranspiration is at a maximum, and much of it is returned to the atmosphere without affecting other components of the hydrologic cycle.

The timing of precipitation and evapotranspiration is important to agriculture in the Western United States because of its effect on available soil water and plant growth. Seasonal variations in soil water, as determined by the

Figure 12.—Average Annual Snowfall in the Western United States



Maximum amounts of snowfall occur at the higher altitudes of the major mountain ranges and in the extreme northern section of the country, a result of the increasing length of the winter season with altitude and latitude. This snowfall represents the primary form of natural water storage for the region.

SOURCE: U.S. Department of the Interior, Geological Survey, *The National Atlas of the United States of America* (Washington, D.C.: U.S. Government Printing Office, 1970).

balance existing between precipitation and evapotranspiration for several selected stations in the region, are shown in figure 13.

The average potential evapotranspiration in the Western United States ranges from an estimated low of 15 to 20 inches in the high mountains of the Pacific Northwest and northern Rocky Mountains to a high of more than 60 inches in small isolated areas in the deserts of Arizona and southern California (fig. 14). It is less than 20 inches along the Canadian border and more than 60 inches in southern Texas. Although potential evapotranspiration and precipitation are independent climatic elements, potential evapotranspiration in arid regions is greater because of the higher daytime temperatures resulting from the absence of clouds and rain. High values in the Colorado and Gila Deserts and in the lower Rio Grande Valley are examples. In the arid sections of the Columbia River Valley between Washington and Oregon, potential evapotranspiration is more than 30 inches, whereas it is only about 20 inches at the same latitude in the Eastern United States.

The variation of potential evapotranspiration through the year follows a uniform pattern in most of the region. It is negligible in the winter months as far south as the Gulf Coastal Plain. It rises to a maximum in July that ranges from 5 inches along the Canadian border to 7 inches on the gulf coast. In some mountainous areas and along portions of the Pacific coast, it does not reach 5 inches in any month.

Infiltration and Percolation

Precipitation that falls on a surface and that is not immediately returned to the atmosphere by evaporation may infiltrate into the surface soil layers. The amount of that which can infiltrate the surface layers is determined largely by the permeability of those layers (the ability to transmit water which is governed by the size and geometry of the spaces within the soil or rock layers) and the amount of water already present in those spaces. Infiltration rates are highest at the beginning of a rainstorm, gradually decreasing with time until some relatively constant value is reached. Some infiltrated water will be retained near the surface by capillary forces. Some will move by gravity flow either toward adjacent stream channels where it will appear as runoff or, more commonly, downward by percolation to the water table where it will enter into ground water storage.

All water that exists below the surface of the Earth in interconnected openings ("interstices") of soil or rock may be called "subsurface water." That part of the subsurface water in interstices completely saturated with water is called "ground water." The upper surface of the zone of ground water is known as the "water table." Between the water table and the surface of the Earth is the "zone of aeration," where the interstices of the soil and rock may contain some varying amount of water, less than total saturation. The water table commonly rises and falls as the availability of water at the surface varies with time (e.g., as a result of climatic change) or as a result of groundwater extraction practices.

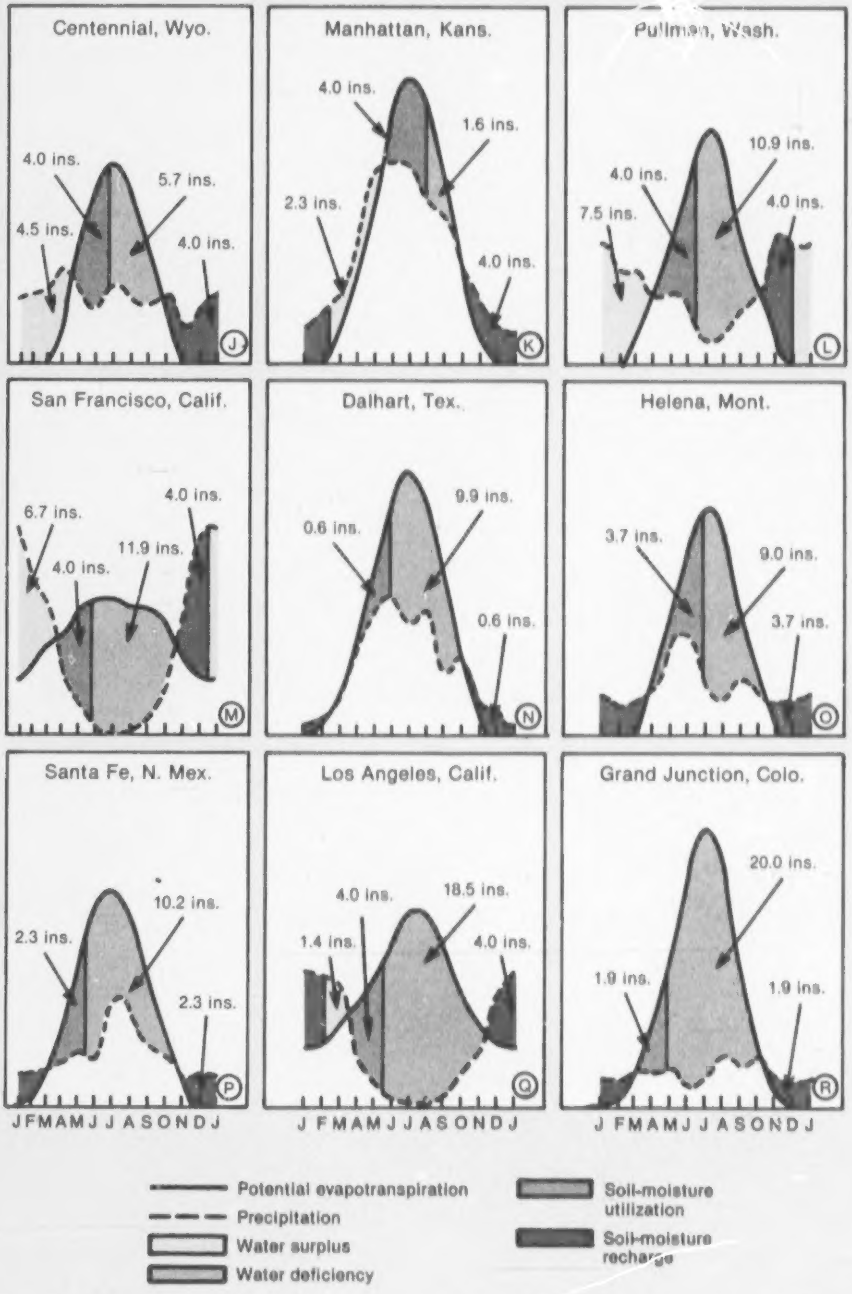
Ground water is not uniformly distributed throughout the West. The major producing aquifers are deposits of unconsolidated sands, gravels, and clays located on preexisting outwash plains or in former lake beds and in the basalts of the Pacific Northwest. In general, the thickness of these aquifers ranges from tens of feet to several thousand feet. Both the amount of water they produce and the quality of that water are extremely variable, even from well to well within the same aquifer. The general locations of the more important ground-water resource regions of the Western United States are shown in figure 15. A detailed discussion of the individual ground-water resource regions is contained in appendix B.

Surface Runoff

Surface runoff, as rivers or streams, generally occurs only after the requirements of evapotranspiration and soil- and ground-water recharge have been satisfied. Where the requirements of either, or both, processes are in excess of annual precipitation amounts, no runoff will take place. Water lost to evapotranspiration is completely lost to runoff. Water that infiltrates into the soil or percolates to ground

Figure 13.—The Relationship Between Precipitation and Potential Evapotranspiration

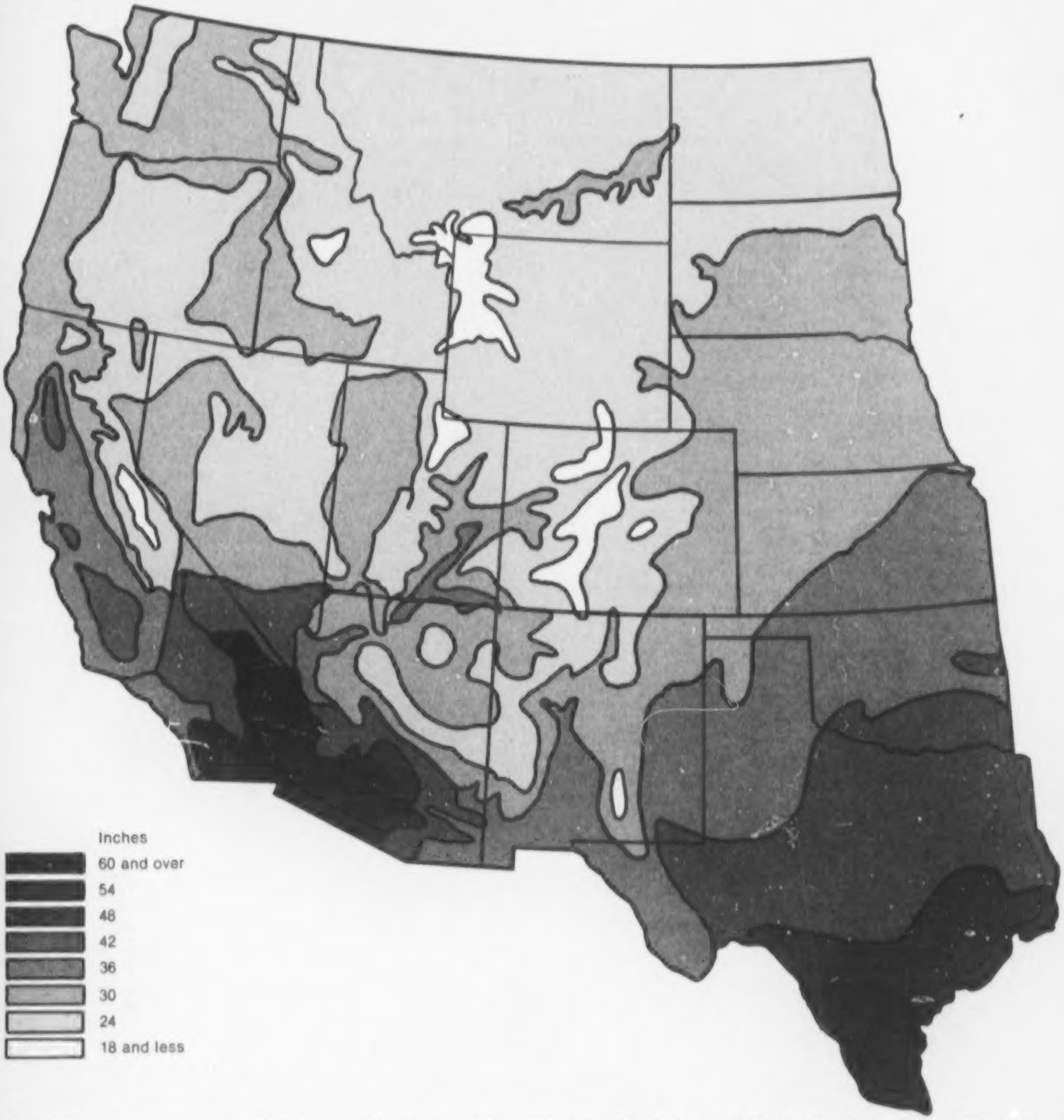
Monthly trends for selected stations in the Western United States show the effects of precipitation and potential evapotranspiration on soil-water conditions. For all stations, precipitation exceeds evapotranspiration only during the winter months. During the summer months, periods of soil-water deficits occur and may last up to 6 months.



SOURCE: R. Thornthwaite, "An Approach Toward a Rational Classification of Climate," *The Geographical Review*, vol. 28 (New York: American Geographical Society, 1948).

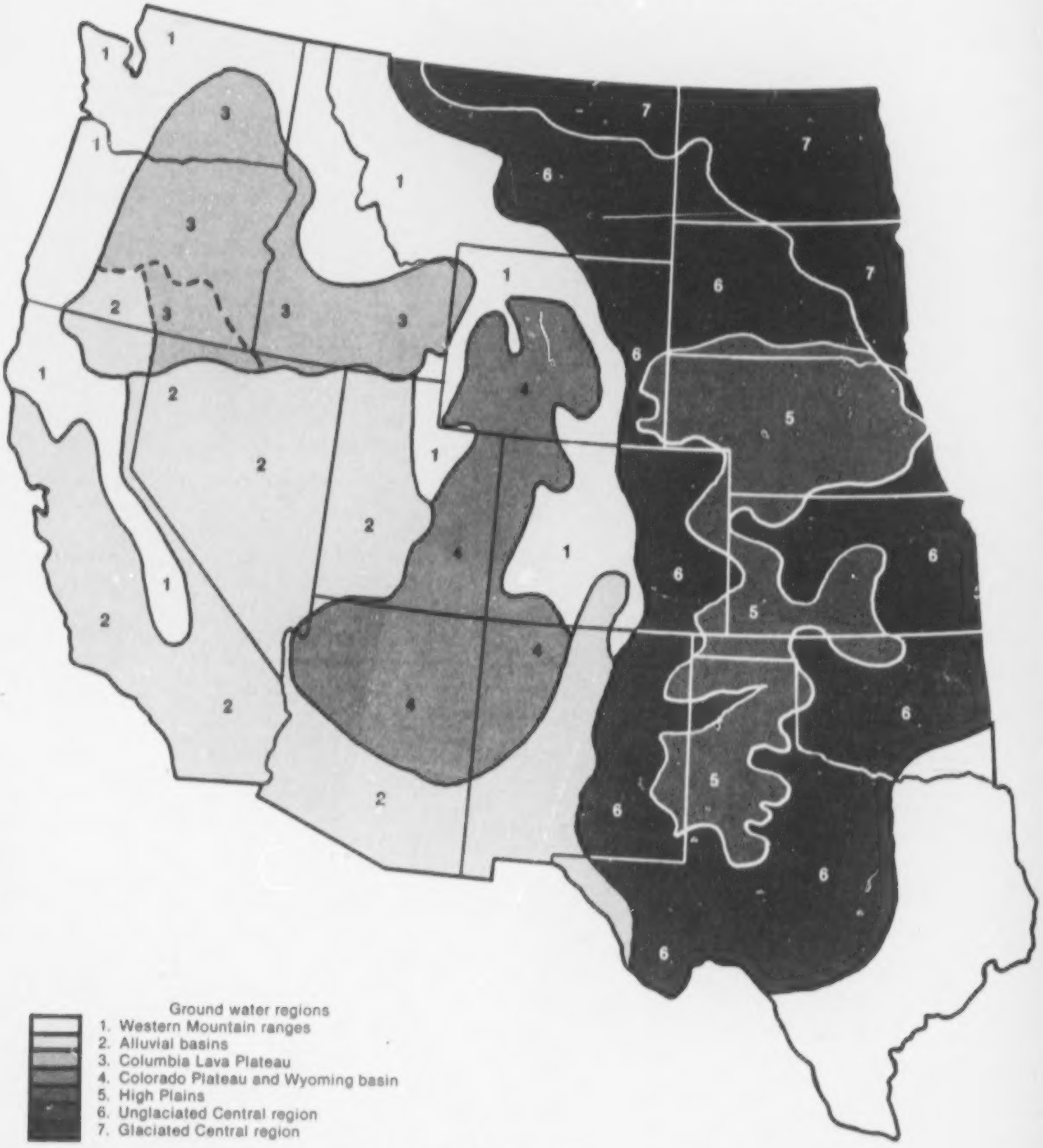
Figure 14.—Potential Evapotranspiration in the Western United States

The pattern of average annual potential evapotranspiration as calculated by Thornthwaite (1948). This figure is included to illustrate a general pattern rather than the actual values for evapotranspiration over the region. Various technologies have been developed to measure total potential evaporation. Actual values will depend on the method of measurement used.



SOURCE: R. Thornthwaite, "An Approach Toward a Rational Classification of Climate," *The Geographical Review*, vol. 28 (New York: American Geographical Society, 1948).

Figure 15.—Major Ground Water Resource Regions of the Western United States


Ground water regions
1. Western Mountain ranges
2. Alluvial basins
3. Columbia Lava Plateau
4. Colorado Plateau and Wyoming basin
5. High Plains
6. Unglaciated Central region
7. Glaciated Central region

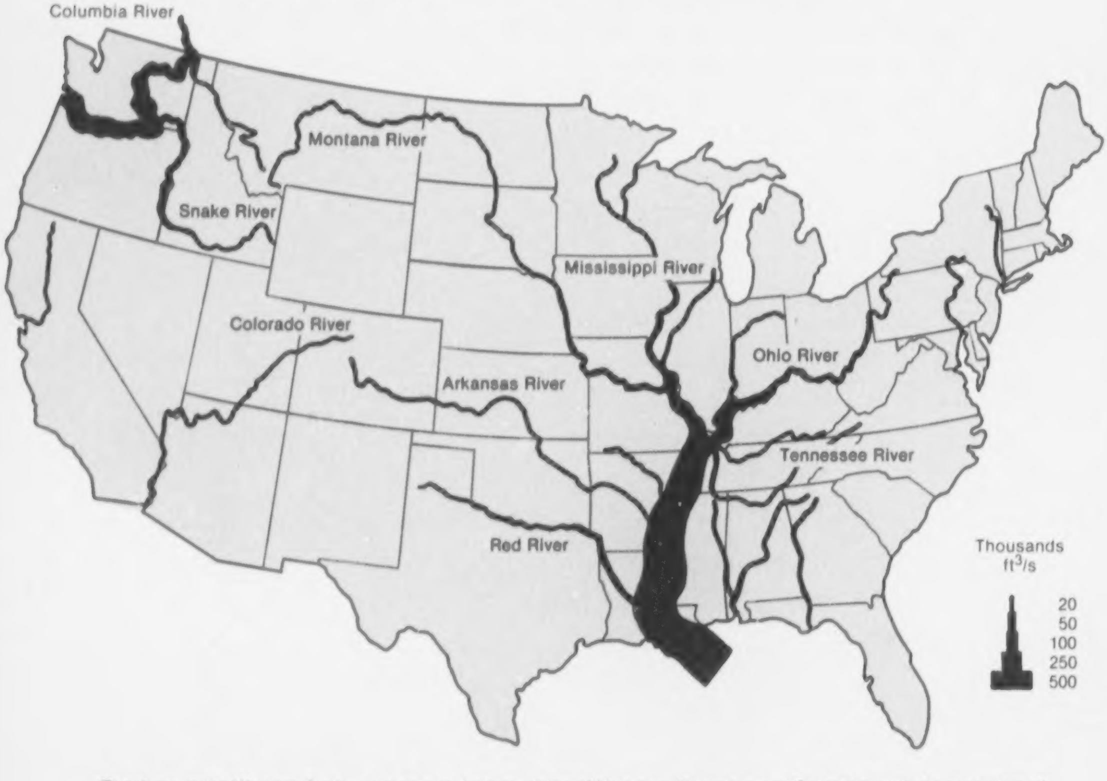
SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980).

water may ultimately appear as surface runoff at some point distant from that at which it fell as precipitation. This will be determined by the amount of transpiration losses, which depletes soil water, and by the ability of the rock formations at a given location to transmit water.

Surface runoff in the Western United States is highly variable, both from one river basin to another and from one time of the year to another. In terms of total volume of annual discharge, the major river system of the region is the Columbia River, which has a mean annual flow in excess of 140 million acre-ft and represents nearly 36 percent of the total volume of surface water available for the entire region. The river system with the smallest annual discharge volume is that of the Rio Grande River, which has an estimated mean annual discharge between approximately 1.3 million acre-ft/yr (1.2 million gal/day) (4) and 6.0 million acre-ft/yr (5.4 million gal/day) (12).

All rivers of the Western United States, except those flowing through the Texas Gulf region, have their headwaters in the mountain ranges of the region or in Canada (fig. 16). The period of peak runoff coincides with the period of spring snowmelt and generally occurs during May or June. There are two exceptions to this general pattern. First, rivers flowing into the Pacific Ocean from the west side of the Sierra and Cascade Mountain ranges in Washington, Oregon, and northern California have

Figure 16.—Average Streamflow for Major U.S. Rivers, 1941-70



The rivers in the Western States originate in the mountains of Montana, Wyoming, and Colorado, with the exception of the Red River in northern Texas and the Columbia River, which flows into the United States from the Rocky Mountains in Canada. One cubic foot per second (cfs or ft^3/s) equals approximately 2 acre-feet per day.

SOURCE: J. Bredehoeft "Physical Limitations on Water Resources in the Arid West," paper presented at a conference on: *Impacts of Limited Water for Agriculture in the Arid West*, Asilomar, Calif., Sept. 28-Oct. 1, 1982.

a peak discharge in January or February. Second, the lower reaches of the Missouri and Snake Rivers have a peak flow in March or April, reflecting the contribution of meltwater produced by the snow deposits of the plains.

The total amount of runoff contained in streams during the spring and summer months varies from over 90 percent of the annual total for some small streams totally dependent on the mountain snowpack to less than 15 percent for streams originating in the Cascade Range, where the contributions to flow are more uniformly balanced between winter rains and spring and summer snowmelt. Figure 17 shows the spatial pattern of the variations in areal contributions to surface runoff in the Western United States. These values are the depth of runoff produced annually and underscore the importance of the mountainous portions of the region in determining water supply.

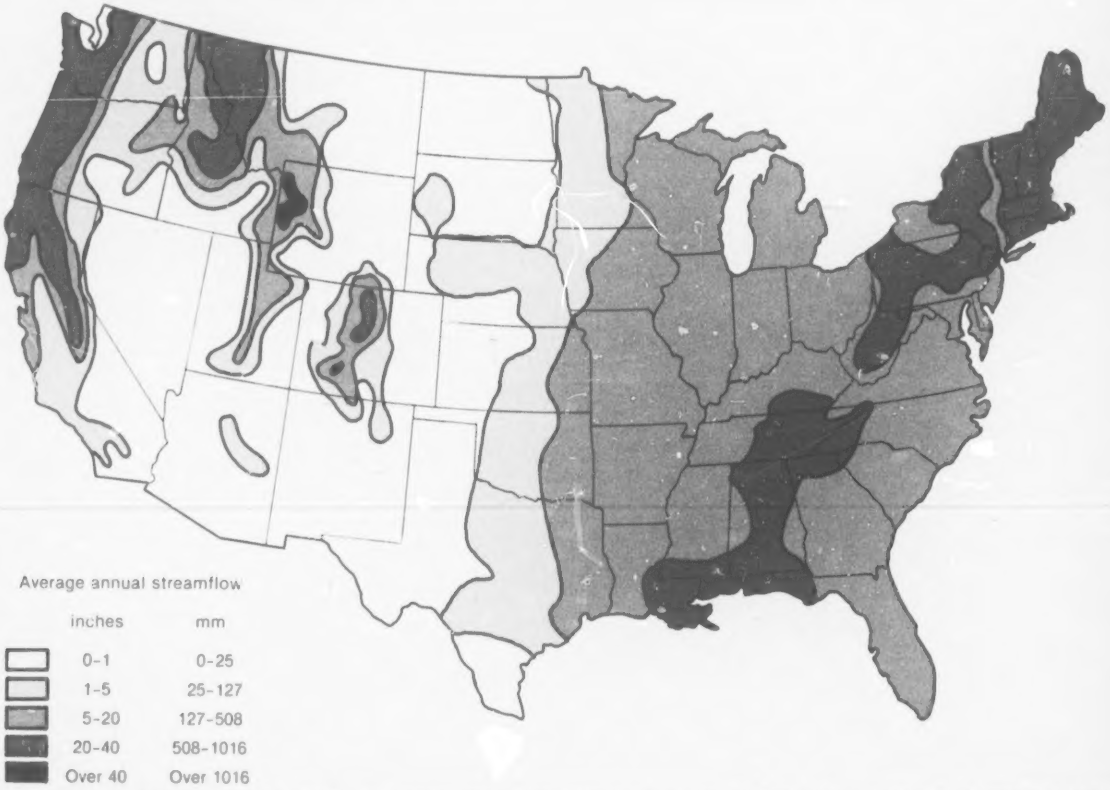
For the Western United States as a whole, surface runoff estimates vary, depending on the data source (4,6,12). The range of estimates is between 515 million and 550 million acre-ft/yr (460 billion to 490 billion gal/day) for the amount of surface runoff that passes through the major river systems of the region.

Variability in the Hydrologic Cycle

Both human-caused and natural variations in the hydrologic cycle affect the timing and

Figure 17.—The Spatial Pattern of Annual Streamflow

With the exception of the Rocky Mountains and the Cascade-Sierra Mountains, much of the Western United States averages less than 1 inch of runoff or streamflow annually.



SOURCE: H. Anderson, M. Hoover, and K. Reinhart, *Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Suply*, USDA Forest Service General technical report PSW-18, 1976.

volume of available water in the Western United States. It is important to recognize that in the Western United States, very few areas remain where the hydrologic cycle operates naturally. Estimates of water availability in any particular component of the cycle must take into account human intervention at the specific site. The impacts of this intervention may vary from site to site. This is due partly to the particular nature of the human activity and partly to the natural hydrologic variability of the area. Thus, it is important to understand the natural variability of Western water resources as well as the variability when modified by humans.

Human Intervention

The primary approaches to accommodate natural variability of Western rivers have been: 1) construction of reservoirs to delay the surface runoff; 2) development of ground water resources; and 3) in limited cases, importation of water from adjacent basins with greater natural supplies. It is estimated that in a natural state the runoff from the 17 Western States would be approximately 590 million acre-ft/yr (12). Human modification of the river systems of the region through the construction of storage reservoirs and water diversions for offstream consumptive uses has reduced natural runoff by approximately 100 million acre-ft/yr. Other components of the hydrologic cycle have also been affected by technological intervention. Human withdrawals from ground water, estimated to be nearly 70 million acre-ft/yr, affect the amount of recharge required to maintain the natural equilibrium (12).

Natural Variability

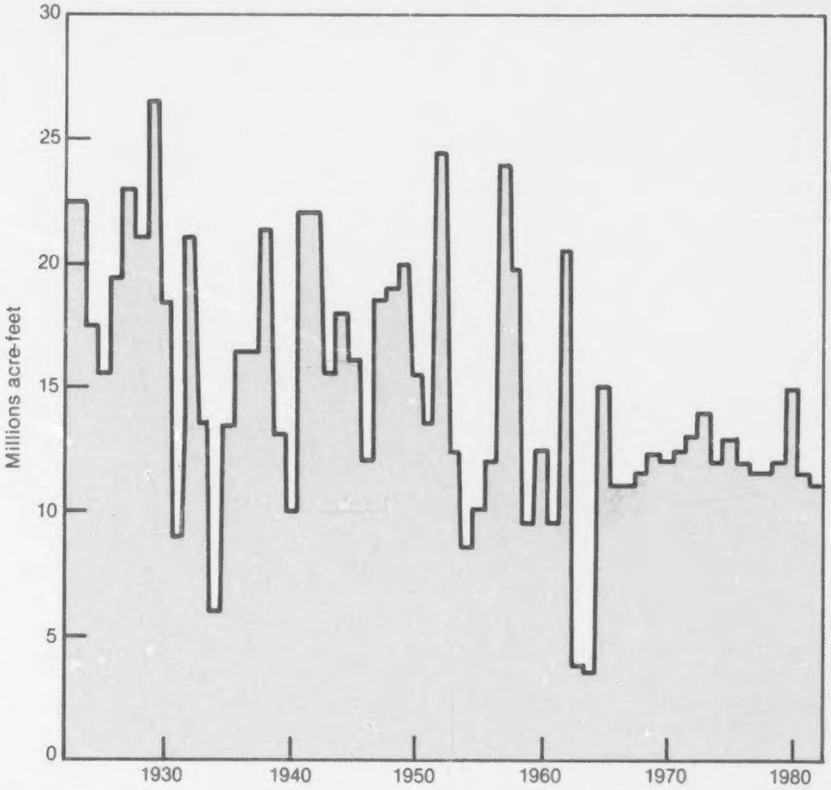
For any given watershed, "wet" and "dry" years are defined with respect to the long-term average streamflow for that watershed. The definitions are based on the percentage of time that given flow volumes occur, as determined by a statistical analysis of the available streamflow record. For the Second National Water Assessment (12), a "dry" year has been defined in terms of the streamflow that would occur, as indicated by a statistical analysis of the data, 20 years out of every century, or 1 year out of 5. The volume of streamflow, as determined in this way, would be much less for a subregion that has a normally low volume of streamflow than for one where this volume was high. Where natural year-to-year variability of streamflow is low, little difference in the flow volume will exist between a "dry" year and a "normal year." For those subregions with a high annual variability, the "dry" year may be a small fraction of the "normal" year flow volume.

It is generally recognized that the annual and seasonal variation in the flow of rivers in the Western United States is significant, often varying by as much as 10 times during a year or during 2 succeeding years. For example, figure 18 reflects the variability of the Upper Colorado River, a pattern typical of Western rivers. Because of such variability, the long-term average annual streamflow volume is not a particularly useful measure of the amount of water that will be available for any given year. Similarly, the monthly volume of flow fluctuates widely, with that occurring during the spring and summer months often representing as much as 90 percent of the total annual flow of many Western rivers (fig. 19). Because of the extreme variability associated with both the annual and monthly streamflow volumes, water-management approaches that are based on a long-term average annual flow will generally be unrealistic for shorter time periods, such as a single year or month during a given year.

In determining the adequacy of existing reservoir storage facilities to meet water demand for agriculture during a series of dry years, it is more useful to know the year-to-year fluctuation of flow and the number of years that this may be expected to drop below an acceptable level than to know only the average flow for some period of years. In determining the extent to which a river will meet seasonal needs of irrigated agriculture, it is more useful to understand the nature of the seasonal variability of streamflow than to know the annual flow volume. Most discussions of the adequacy of water supplies in the Western United States

Figure 18.—The Annual Variability of Steamflow Volume, Upper Colorado River, 1920-80

The year-to-year variability of most Western rivers is high, as typified by the Upper Colorado River. Where water is allocated on the basis of some long-term mean-flow volume, there will be insufficient water to meet that allocation during many years. The decreased variability of the Colorado River shown on this figure beginning in the mid-1960's results from the construction of dams and reservoirs.



SOURCE: Office of Technology Assessment, compiled from National Water Data Exchange (NAWDEX), U.S. Geological Survey, 1983.

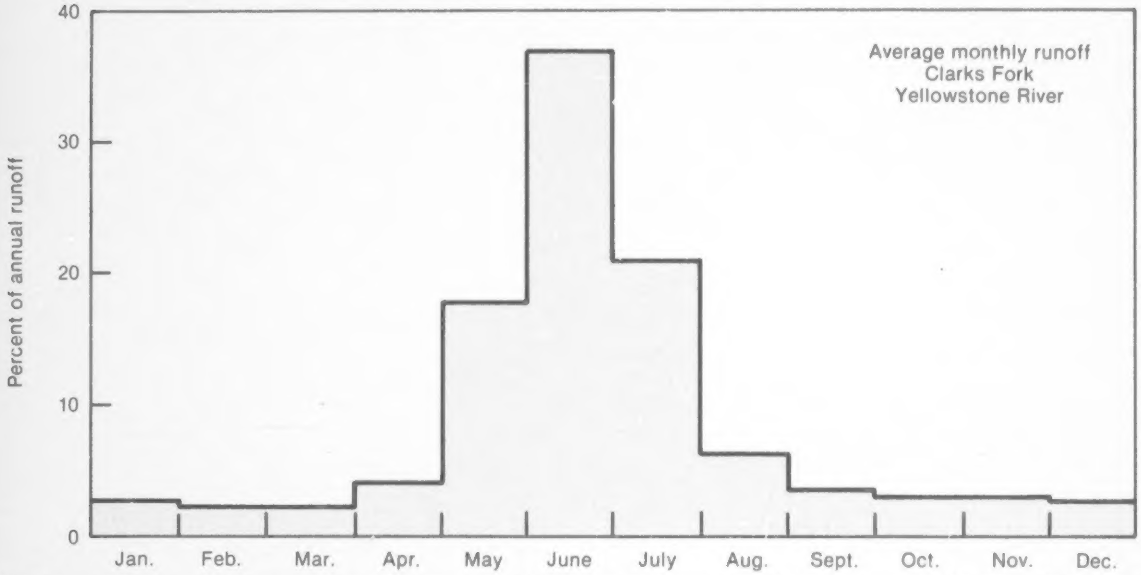
have been developed in terms of annual mean values (e.g., 4).

Estimates of future water availability, including that for all types of agriculture, must be based on some estimates of climatic trends. Climatic fluctuations affect all components of food-producing ecosystems. Changes in food production can be caused by the effects of weather on pests, pathogens, weeds, and crop plants and by altering water-supply and water-use patterns. Western agriculture has developed during a particularly warm period in recent climatic history (7). Climatic records show that climate has varied in the past, however, and significant fluctuations have occurred in recent history.

In addition to the natural variability of climate, there is growing speculation about human-induced climatic change. These include: 1) the decreasing pH (increasing acidity) of rainfall, which may be caused by emissions from burning fossil fuel; 2) the gradual increases in the atmospheric fraction of carbon dioxide (CO_2) and other infrared absorbing gases, also largely a result of increased burning of fossil fuels; and 3) the associated changes in water quality, quantity, and, specifically in the case of the infrared absorbing gases, air temperature increases.

Figure 19.—Average Monthly Runoff, Clarks Fork, Yellowstone River

Natural seasonal variability in the volume of flow of most Western rivers is large. In come cases, the spring and early summer snowmelt peak flow of Western rivers represents as much as 90 percent of the annual volume of flow of these rivers.



SOURCE: J. Bredehoeft, "Physical Limitations on Water Resources in the Arid West," paper presented at a conference on: *Impacts of Limited Water for Agriculture in the ARid West*, Asilomar, Calif., Sept. 28-Oct. 1, 1982.

Long-term agricultural planning and policymaking must be undertaken with the knowledge that some climatic change is inevitable. The geographic extent of any changes in climate will be related to the frequency of the change. Changes on the order of a few years to a few decades will be more localized geographically than will those that persist for decades. To the extent that the ability to predict climatic trends is limited, so too is the ability to determine continuing availability of water for agriculture in the Western United States. As stated in a National Research Council report (5), "Our knowledge of mechanisms of climate change is at least as fragmentary as our data." An improvement in the existing data base, as discussed in the next section, should be a first step toward improving the ability to factor climatic trends into agricultural planning.

Measurement

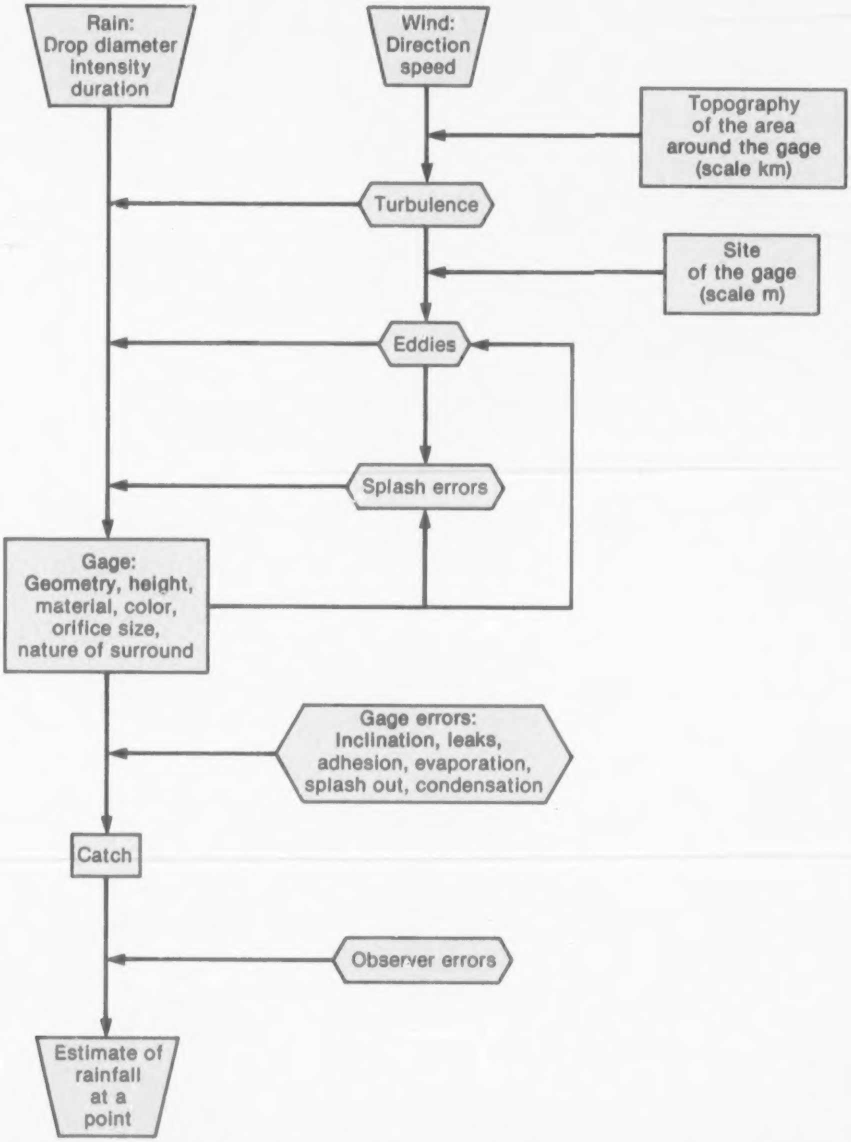
Water is in continuous movement through the hydrologic cycle. A variety of measurement techniques are required to monitor this movement. While all hydrologic processes take place over the surface area of a region, measurements of elements of the hydrologic cycle such as evapotranspiration or precipitation are made at discrete points within that region. In order to determine the volume of water involved in these transfer processes, it is necessary to combine the individual point measurements into a spatial pattern from which volume can be estimated.

Some of the problems inherent in all point measurements may be illustrated by those associated with determining the amount of rain that falls at a point. The uncertainties involved in even this apparently simple measurement are illustrated in figure 20. In developing average values representative of a particular place or time, the selection of the data to be included or excluded is critical.

Only surface runoff may be measured as an arcal value, since all the surface runoff from a region must pass through a surface-gaging station. Thus, for surface water, the location selected for the placement of the gaging sta-

Figure 20.—Potential Errors in Water Measurements

Errors can occur in the measurement of any of the components of the hydrologic cycle and can affect the accuracy of the data.


Rain:
Drop diameter
intensity
duration
Wind:
Direction
speed
Topography
of the area
around the gage
(scale km)
Turbulence
Site
of the gage
(scale m)
Eddies
Splash errors
Gage:
Geometry, height,
material, color,
orifice size,
nature of surround
Gage errors:
Inclination, leaks,
adhesion, evaporation,
splash out, condensation
Catch
Observer errors
Estimate of
rainfall
at a
point

SOURCE: R. Ward, *Principles of Hydrology* (New York: McGraw-Hill, 1975).

tion is critical. In many cases, the proximity of a gaging station to the point of use determines the usefulness of the data obtained.

In addition to the uncertainties of point measurements for estimating spatial volumes, there are uncertainties in developing time trends from estimates of selected time periods. The amount of water in each of the solid, liquid, and vapor phases changes naturally with time. In order to reduce this continuous variation to terms meaningful for analysis, it is common to present data pertaining to elements of the hydrologic cycle as averages for selected time periods. Thus, concepts such as "mean annual precipitation" or "mean monthly streamflow" have been introduced to simplify data manipulation. Ultimately, this simplifying process has produced concepts such as "the average precipitation for Arizona" or the "average runoff of the Upper Colorado River." In both cases, a large amount of spatial and temporal variation in the natural processes has been condensed in order to compare the environments of two or more hydrologic areas.

Also, as discussed above, various components of the hydrologic cycle are modified by human intervention. For example, as water is stored in reservoirs or removed from the surface or subsurface and applied to some use such as irrigation, the fundamental natural relationships are altered. Virtually all the technologies discussed in this assessment are designed to modify to some degree the distribution of water within the natural hydrologic cycle. The degree to which the hydrologic cycle has been modified varies widely among the river basins of the Western United States. This human-caused variability further complicates collecting, interpreting, and developing useful averages from existing data.

In developing average values, short- and long-term syntheses are prepared. Short-term syntheses relate to daily, monthly, or annual fluctuations and are referred to as "climate" or as the "hydrologic regime" of a region. Climate is the average course or condition of the weather at a place over a period of years, as exhibited by air temperature, wind velocity, and precipitation. Taken together, these simple measurements of complex processes of water and energy transfer estimate the disposition of water among the various phases of the hydrologic cycle. These short-term syntheses are important in making decisions concerning water availability and use from one year to the next or from one growing season to the next.

Long-term syntheses involve the concept of climate change over decades, centuries, or longer. This type of synthesis uses the average values developed from short-term data collected over a few decades. Long-term change is identified as the climate slowly becomes wetter or drier, warmer or cooler. An example of climate change that has been important for recent water planning involves the value for the average flow of the Colorado River used in the Colorado River Compact (discussed in ch. V). Runoff in this river during the period used to determine an "average" flow for allocating the waters of the Colorado River was higher than the average annual flow that now exists. A change in the climate of that river basin has gradually decreased the flow of the river below the value used in the allocation of water between the upper and lower basin States.

Decisions on water availability and use in the Western United States must reflect uncertainties associated with measurement. To some extent, all measurements of the elements of the hydrologic cycle are estimates. As concluded by another OTA assessment, estimates of water volume or time-trends from point estimates have varying degrees of reliability (8). The reliability of these estimates will be determined by: 1) the ability of an instrument to accurately measure the processes involved; 2) the extent to which the measurement site is representative of the area in which it has been established, and 3) where point-source data (e.g., precipitation measurements) are involved, the number of gages that are combined to develop the estimate. This reliability is also related to the length of record and the assumption of no climate change during the period of record.

WATER PLANNING, DATA COLLECTION, AND ANALYSES

Evolution of the Federal Role

The Federal Government has been involved in water-data collection and water-resources planning and analyses since the formation of the Nation. It intensified its activities with the passage of the 1902 Federal Reclamation Act. More than 20 major national studies or programs have been undertaken since then for the purpose of defining and guiding Federal activity in this complex and important area (13).

Some of the more publicized programs have occurred since the 1940's when a major focus was the development of multipurpose river basin plans and the analysis of river basin problems. One reason that the Federal Government became involved was that river basins and aquifers (basic water-planning units) almost always cover parts of more than one State and require a broad regional geographic perspective. In 1943, the Federal Inter-Agency River Basin Committee (FIARBC) was established as a coordinating body for agencies involved with preparing river basin surveys. After World War II, FIARBC developed regional committees for some of the major river basins, including the Missouri and Columbia basins in the West. In 1959 Congress established a Senate Select Committee on Water Resources. The work of this committee was later translated into two major acts, the Water Resources Research Act of 1964 (Public Law 88-379) and the Water Resources Planning Act of 1965 (Public Law 89-90), which has provided the basis for much recent Federal involvement in water. The Water Resources Council (WRC) created under the latter act produced the first National Water Assessment in 1968.

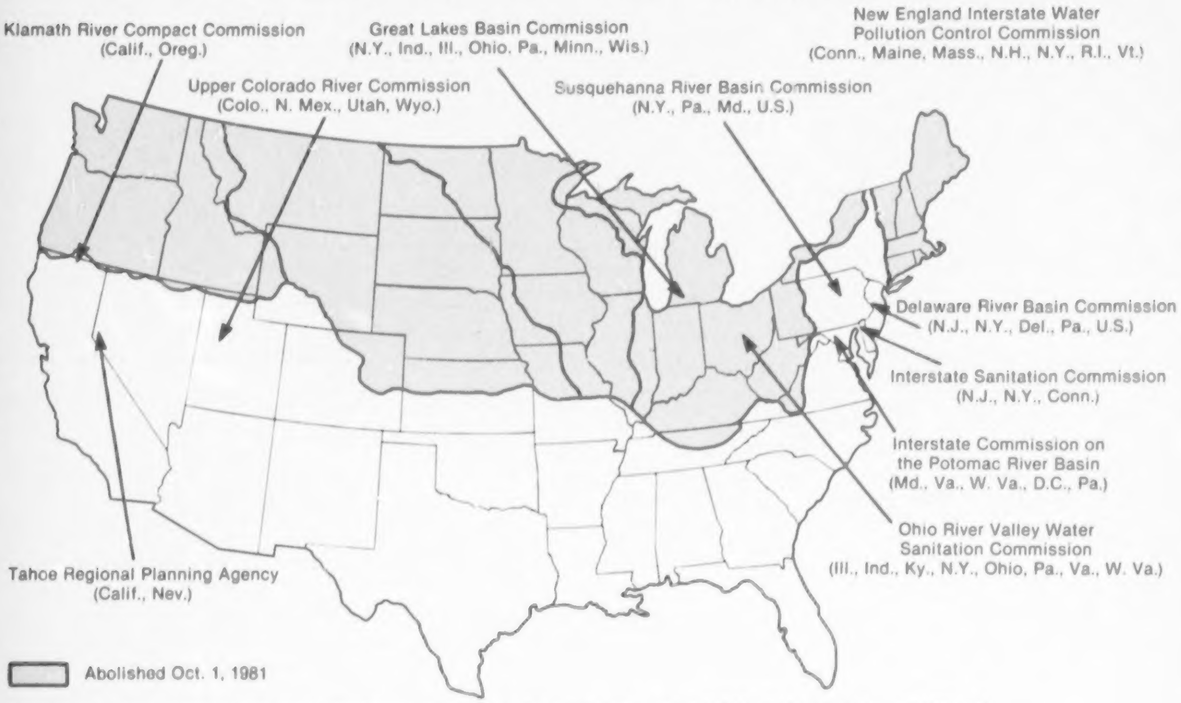
In the 1970's, attempts continued to better define a Federal role in water-resources planning. A National Water Commission, established by an Act of Congress (Public Law 90-515), produced a report to the President and to Congress in 1973, *Water Policies for the Future.* This report outlined several alternative futures and possible actions for water-resources development to 2020 in light of the Nation's water-resource supplies and needs. WRC produced a second national assessment in 1978 that compiled data on the Nation's water resources to determine the adequacy of water supplies for meeting anticipated future needs in the 21 major water-resources regions of the United States. Then, during the Carter administration, an intensive review of national water policy and several water-policy initiatives were begun, including increased attention to water conservation and environmental quality.

The early 1980's brought a major reversal in Federal water involvement from that which had developed over the past two decades. President Reagan removed Federal sponsorship of WRC, the river basin commissions (fig. 21), and the State water research institutes previously supported through DOI's Office of Water Research and Technology. This action effectively caused the demise of these institutions except in a few cases where States have attempted to assume full financial responsibility for operations.

These earlier broad-based Federal attempts to integrate water-resource research, policy, and planning have not been replaced. The Reagan administration created a small Office of Water Policy in DOI in 1982 to serve the Department Secretary. Then in March 1983, DOI announced that it would prepare annual National Water Summary reports in a simplified and condensed form for decisionmakers as an alternative to previous detailed national water assessments.

Currently, no additional funds are available for this activity. All costs for data collection and analysis are to be absorbed within existing budgets of the Department and of other agencies that will be expected to volunteer staff and equipment to respond to data requests. Also, these summaries will not project future trends. That function will be a responsibility of the individual States. According to the Department, this program is in furtherance of the present administration's policy "that responsibility for

Figure 21.—River Basin Commissions and Other Regional Water Agencies Abolished in 1981


Klamath River Compact Commission (Calif., Oreg.)
Great Lakes Basin Commission (N.Y., Ind., Ill., Ohio, Pa., Minn., Wis.)
New England Interstate Water Pollution Control Commission (Conn., Maine, Mass., N.H., N.Y., R.I., Vt.)
Upper Colorado River Commission (Colo., N. Mex., Utah, Wyo.)
Susquehanna River Basin Commission (N.Y., Pa., Md., U.S.)
Delaware River Basin Commission (N.J., N.Y., Del., Pa., U.S.)
Interstate Sanitation Commission (N.J., N.Y., Conn.)
Interstate Commission on the Potomac River Basin (Md., Va., W. Va., D.C., Pa.)
Ohio River Valley Water Sanitation Commission (Ill., Ind., Ky., N.Y., Ohio, Pa., Va., W. Va.)
Tahoe Regional Planning Agency (Calif., Nev.)
▭ Abolished Oct. 1, 1981

SOURCE: K. C. Flynn, "Loss of River Basin Commissions Forces a Look at Alternatives," *Journal WPCF*, vol. 54, No. 1, January 1982, p. 9.

water resources management rests with the States" (9).

Data Collection and Analysis Responsibilities

A fundamental barrier to any institutional attempt to assess the nature and magnitude of potential water-related problems facing Western arid/semiarid lands is the nature and adequacy of the water-resources data base. Basic hydrologic processes are complex, and the data required to evaluate water available at a particular point in the process are often unavailable in the form needed.

Responsibilities for water-related data collection, analysis, dissemination of information based on those data, and planning are scattered widely among a number of Federal and State agencies. Most of the regionally useful data have traditionally been collected by agencies of the Federal Government (table 11). In recent years individual States have begun developing a data collection and interpretation capability to fulfill local needs.

Among Federal agencies, the lack of a single or coordinated mechanism for data collection and analyses has produced a number of data bases and interpretations with varying degrees of compatibility.* Beginning in 1973, a national confederation of water-oriented organizations was formed to improve access to water data (10). The resulting program, the National Water Data Exchange (NAWDEX), became operational in January 1976, with the U.S. Geological Survey (USGS) having lead-agency responsibility through its Office of Water Data Coordination. NAWDEX can provide data directly or a listing of those organizations responsible for the data, together with a description of the

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*For an analysis of water models, see the OTA assessment (8).

Table 11.—Federal Water-Data Collection Agencies[a]

	Government agencies						Independent agencies			
In-house data programs	USDA	DOC	DOD	DOE	DOI	DOT	EPA	IBWC	NRC	TVA
Surface water	X	X	X	X	X	X	X	X	—	X
Ground water	X	—	X	X	X	X	X	X	—	X
Water quality	X	X	X	X	X	X	X	X	—	X
Water use	X	X	X	X	X	—	—	—	—	—
Environmental impact	X	—	X	X	X	X	X	—	—	X
Ecology	X	—	X	X	X	X	X	—	—	X
Management effects	X	—	X	X	X	X	X	—	—	X
Basin studies	X	—	—	—	X	X	X	—	—	X
Real-time sensing	X	X	X	—	X	X	—	—	X	
Remote sensing	X	X	X	—	—	X	X	—	—	X
Data sensing	X	—	X	X	X	—	X	—	—	X
Instream use	X	—	—	—	X	—	—	—	—	—
Water rights	X	—	—	—	X	—	—	—	—	—
Floods	—	X	—	—	X	X	—	—	—	X
Energy	—	—	—	X	X	—	—	—	X	—
Nuclear	—	—	—	X	X	—	X	—	X	—
Precipitation quality	—	—	—	—	X	—	X	—	—	X

KEY: USDA—U.S. Department of Agriculture; DOC—Department of Commerce; DOD—Department of Defense; DOE—Department of Energy; DOI—Department of the Interior; DOT—Department of Transportation; Independent agencies: EPA—Environmental Protection Agency; IBWC—International Boundary & Water Commission; NRC—Nuclear Regulatory Commission; TVA—Tennessee Valley Authority.

[a] For the 1981-82 fiscal year, 26 Federal agencies, representing six departments and four independent agencies, collected water resource data. These efforts have produced a diffuse data base, confused agency responsibilities for water measurements, and often introduced varying data collection techniques which produce data incompatibility.

SOURCE: U.S. Department of the Interior, Geological Survey, Office of Water Data Collection, *Plans for Water Data Acquisition by Federal Agencies Through Fiscal Year 1983* (Reston, Va.: 1982), p. 7.

characteristics of the data. Through NAWDEX, it is possible to obtain basic data from several data systems:

- the Water Data Storage and Retrieval (WATSTORE) System of USGS;
- the Storage and Retrieval (STORET) System of EPA;
- the Environmental Data and Information Service (EDIS) of the National Oceanic and Atmospheric Administration (NOAA);
- the Water Resources Scientific Information Center (WRSIC) of USGS; and
- various State agencies, such as the Texas Natural Resources Information System (TNRIS), the Nebraska Natural Resources Information System (NNRIS), and the Utah Division of Water Rights.

NAWDEX is a significant improvement over the previous method. It was formerly necessary to obtain the published lists of data from each responsible agency. However, it is still necessary to analyze any data obtained through the NAWDEX system, since the system mainly provides data storage and retrieval without extensive analytical capabilities.

For the purposes of this assessment, OTA has relied heavily on preexisting analyses, rather than on the data base itself. These analyses, consisting of reports by the National Water Commission (6), WRC (12), and USGS (e.g., 4) provide summaries of many pertinent aspects of the hydrologic regime of the Western United States.

There are, however, discrepancies among the summarized data contained in these reports (tables 12 and 13). For assessment purposes, it has been assumed that these discrepancies have arisen from the nature of the assumptions made in the analysis of basic data and from the use of different data bases rather than from faulty analytical procedures. It has not been possible to resolve these differences, and they can only be noted here. In some cases, these discrepancies are great enough to make it difficult or impossible to reach any firm conclusion about the total availability of water for

Table 12.—Estimates of Average Annual Runoff in the Western United States, 1975
(in billion gallons per day [bgd] and million acre-feet [maf])

Estimates of average annual runoff in the Western United States for 1975, show a wide range of data. Published estimates for individual regions varied by more than 400 percent. Until discrepancies such as these can be eliminated, it will be difficult to reach valid decisions on water resource management.

	WRC		USGS		
Region	bgd	maf	bgd	maf	% WRC
10 Missouri	44.1	49.4	54.0	60.5	122
11 Arkansas-White-Red	62.6	70.1	73.0	81.8	117
12 Texas-Gulf	28.3	31.7	32.0	35.8	113
13 Rio Grande	1.2	1.3	5.0	5.6	417
14 Upper Colorado	10.0	11.2	13.0	14.6	130
15 Lower Colorado	1.6	1.8	3.2	3.6	200
16 Great Basin	2.6	2.9	7.5	8.4	288
17 Pacific Northwest	255.3	285.9	210.0	235.2	82
18 California	47.4	53.1	62.0	69.4	131
Regions 10-18	453.1	507.5	459.7	514.9	101

SOURCES: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 3, table II-6.
C. Murray and E. Reeves, *Estimated Use of Water in the United States in 1975*, U.S. Geological Survey Circular 765, 1977, p. 18.

Table 13.—Estimates of Total Water Withdrawals in the Western United States, 1975
(in billion gallons per day [bgd] and million acre-feet [maf])

Estimates of total water withdrawals in the Western United States for 1975 were made by the Water Resources Council and U.S. Geological Survey. A wide range exists in the data, a result largely of data selection criteria and assumptions used in the interpretation of those data. Until these differences are resolved, it will be difficult to reach an agreement on the nature of the water problems in the area.

	WRC		USGS		
Region	bgd	maf	bgd	maf	% WRC
10 Missouri	38.0	42.6	35.0	39.2	92
11 Arkansas-White-Red	13.0	14.6	15.0	16.8	115
12 Texas-Gulf	26.0	29.1	22.0	24.6	84
13 Rio Grande	6.3	7.1	5.4	6.1	86
14 Upper Colorado	6.9	7.7	4.1	4.6	59
15 Lower Colorado	8.9	10.0	8.5	9.5	96
16 Great Basin	8.0	9.0	6.9	7.7	86
17 Pacific Northwest	37.6	42.1	33.0	37.0	88
18 California	54.2	60.7	51.0	57.1	94
Regions 10-18	198.9	222.9	180.9	202.6	91

SOURCES: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), *Summary*, vol. 1, p. 25.
C. Murray and E. Reeves, *Estimated Use of Water in the United States in 1975*, U.S. Geological Survey Circular 765, 1977, p. 19.

some water resource regions or about the regional usefulness of a given technology designed to increase water-use efficiency.

Some form of coordinating mechanism is essential for collecting and synthesizing available data and communicating results to a wide audience. The necessity for such an organization is doubly important inasmuch as water is an extremely dynamic resource. Because of this dynamism, both the data base and the assumptions applied to its interpretation must be continually tested if both are to remain relevant to the solution of emerging problems.

WATER USE IN THE WESTERN UNITED STATES

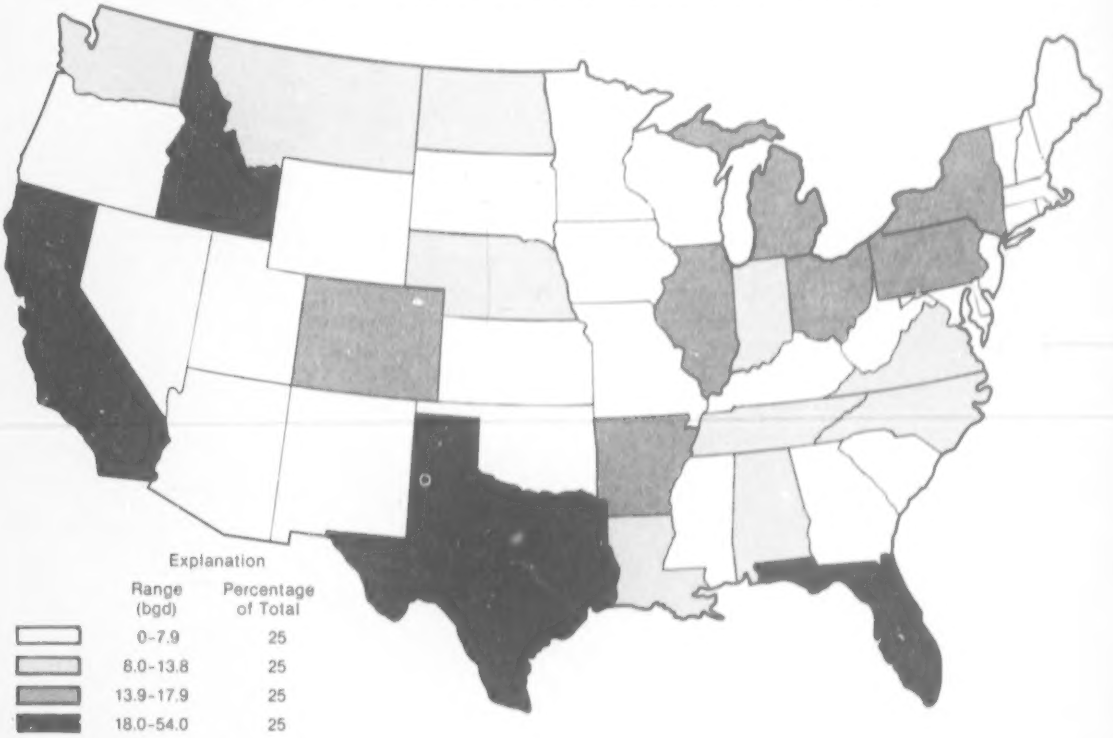
Relationship Between Supply and Demand

Depending on the areas, from 70 to 90 percent of the total annual surface runoff and ground-water recharge in the Western United States occurs during spring and summer. It is derived largely from the melting of the mountain snowpack of the region (e.g., 2). The contribution of snowmelt may be as low as 30 percent of the annual total flow in the mountains of western Washington State, where the precipitation peak occurs as a result of rainfall during the winter months, to as high as 90 percent along tributaries of the upper Missouri or Colorado Rivers.

Water is "consumed" when it is withdrawn and used in such a way that it is no longer available for additional uses. This means it has been either evaporated, transpired, incorporated into products or crops, consumed by livestock or humans, or otherwise removed from the water environment. Water is "used" but not consumed when it is withdrawn and returned to a river, as with irrigation return flows, hydroelectric energy generation, or maintenance of instream flow requirements.

According to USGS data, in 1975, water withdrawn from surface and ground water supplies in the Western United States averaged 3,000 gallons per person per day for a population of 50.8 million people. The total withdrawal was approximately 170.7 million acre-ft. A comparison of total water withdrawal, by State, is shown in figure 22. Water use in the Western and Eastern States is compared in table 14.

Figure 22.—Total Offstream Water Withdrawals, by States, 1980



SOURCE: W. Solley, E. Chase, and W. Mann, *Estimated Use of Water in the United States in 1980*, U.S. Geological Survey circular 1001, 1983.

Table 14.—Per Capita Water Use in the Eastern and Western United States

These figures represent both water withdrawals and consumptive uses.

	Contiguous United States water resources regions		
	Eastern (9 regions = 31 States)[a]	Western (9 regions = 17 States)[a]	United States (50 States, District of Columbia, Puerto Rico, and Virgin Islands)
Population, in millions:			
Total	155.7	69.1	229.6
Served by public supplies	123.5	58.1	186.1
Self supplied (rural)	32.2	11.0	43.5
Per capita water use, in gallons per day:			
Offstream use:			
Total withdrawals[b]	1,600	2,900	2,000
Public supplies:			
All uses[c]	160	230	180
Domestic and public uses and losses[c]	100	150	120
Rural domestic use[d]	73	98	79
Irrigation[b]	82	2,000	660
Self-supplied industrial[b]	1,300	660	1,100
Consumptive freshwater use[b]	120	1,200	450
Instream use:			
Hydroelectric power[b]	8,900	27,000	14,000
Total offstream and instream use[b]	10,000[e]	30,000[e]	16,000

[a] Approximate boundaries.
[b] Based on total population.
[c] Based on population by public supplies.
[d] Based on rural population.
[e] Totals may not add due to rounding.

NOTE: All per capita data calculated from unrounded figures and rounded to two significant figures.

SOURCE: W. Solley, E. Chase, and W. Mann, *Estimate Use of Water in the United States in 1980*, U.S. Geological Survey Circular 1001, 1983.

Also according to USGS data, the per capita consumption of water in the Western United States averages 1,300 gallons per person per day, or approximately 145 million acre-ft. Eighty-five percent of the total withdrawals are for irrigated agriculture. The amount of this irrigation withdrawal that is consumed ranges from over 80 percent in the Texas-Gulf Water Resources Region to slightly more than 30 percent in the Pacific Northwest and Upper Colorado River Water Resources Regions. The average water consumed by irrigated agriculture for the nine western WRC regions is 56 percent of that withdrawn (4,12). Aspects of water supply, withdrawal, and consumption in the nine water-resource regions of the Western United States are given in table 15.

A variety of problems is encountered in defining the amount of water actually available for use in the Western United States. The most obvious one is determining the total volume of water that passes annually through the hydrologic cycle of the region. A second measure of water availability, that of determining the quantity of water that is used "consumptively," and thus made unavailable for any subsequent uses, is becoming a less certain indicator of water availability because, increasingly, nonconsumptive uses such as hydroelectric generation or instream flow requirements compete with consumptive uses such as irrigated agriculture. It is apparent that the same unit of water cannot generate electricity and concurrently be used for irrigation. Increasingly, decisions about the timing of storage and release of water from regional reservoirs will be made in the context of diverse and often conflicting uses.

Water Supply and Use Patterns

Annual Estimates of Supply

Attempts to estimate a "dependable" supply for the purposes of water planning and management are partially subjective, involving the relationship between supply and use at the time of use. Total annual streamflow is not a useful

Table 15.—Water Supply and Use, Including Off-Channel and Hydroelectric Generation, by Region

Water resources region	Area (000 mi²)	Average runoff[a]		Normal reservoir storage[b] (maf)	Established dependable supply[a] (maf)	Withdrawals all sources[c] (maf)	Consumption[c] (maf)	Ground water withdrawn[c] (maf)	Hydroelectric generation[c] (maf)
		Maf/yr	Inches/year						
10	515	60.5	2.2	83.4	33.6	43.7	17.9	13.4	160.0
11	265	81.8	6.0	30.3	22.4	26.9	10.7	10.6	70.0
12	175	35.8	3.9	23.5	19.0	19.0	7.3	5.7	8.7
13	136	5.6	0.8	7.8	3.4	5.3	2.7	2.1	1.2
14	110	14.6	2.5	10.2	14.6	9.5	2.6	0.2	18.0
15	137	3.6	0.5	61.3	2.2	9.7	5.5	5.0	43.0
16	185	8.4	1.0	3.8	10.1	8.4	4.4	1.8	6.2
17	271	235.0	16.0	54.8	78.4	38.1	13.4	9.2	1,700.0
18	120	69.4	9.0	40.0	31.3	60.5	28.0	23.5	83.0
Total	1,914	514.9	4.7	315.0	215.0	221.1	97.5	71.6	2.090.1
Percent of conterminous U.S.	63%	38%	56%	70%	37%	44%	57%	73%	56%

NOTE: Partial figures may not add because of independent rounding.

[a] C. Murray and E. Reeves, *Estimated Use of Water in the United States in 1975*, U.S. Geological Survey Circular 765, 1975.

[b] U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 2, pt. IV, 1978, p. 13.

[c] W. Solley, E. Chase, and W. Mann, *Estimated Use of Water in the United States in 1980*, U.S. Geological Survey Circular 1001, 1983.

indicator of water availability for most uses because a considerable amount of seasonal and year-to-year variation exists in the volume of flow of the rivers of the Western United States. Water supply at any point is a result of a complex interaction between withdrawal activities and return flows all along the system, involving some consumptive uses and some instream, nonconsumptive uses. Moreover, these use patterns are subject to change as the needs or desires of society change.

Analyses of the adequacy of water supplies are commonly based on the annual amounts of consumptive water use and streamflow. USGS has developed estimates of dependable annual supply for the water-resource regions (14), based on a statistical analysis of streamflow records and an evaluation of the degree to which reservoir storage assists streamflow in maintaining a satisfactory available supply. These estimates do not relate specifically to the needs of irrigated agriculture because they do not reflect the relationship between supply and use patterns during summer when demand for irrigation water is at a maximum. They do, however, serve as a useful first approximation of water availability in the West.

According to the USGS statistical analysis of streamflow and storage, the Missouri and Arkansas-White-Red regions have moderately large water supplies and favorable supply-to-demand relationships. In the Texas-Gulf region, withdrawals are greater than the estimated dependable supply and have exceeded the flow in 90 years out of 100, and excess demand is made up largely from ground water and water reuse. Consumption of water in the Rio Grande region is greater than dependable supply, while in the Upper Colorado region, supply exceeds demand. Both water withdrawals and consumption in the Lower Colorado region exceed the supply originating in that area. Excess demand is met by inflow of water from the Upper Colorado region, importation of surface water, repeated withdrawals of water, and ground water "mining." Large ground water withdrawals are characteristic of the Texas-Gulf, Rio Grande, Arkansas-White-Red, Lower Colorado, and California regions.

A slightly different approach to estimate water supply and demand has been used by another USGS scientist who defines a "relative water depletion" index as the total consumptive use plus any water exported from each basin, divided by the total supply (1). Ground water mining was excluded from this USGS calculation.

Bredehoeft found that for:

1. most of the lower Colorado River basin, southern California, and most of Nevada, depletion exceeds 100 percent of the annual surface supply;

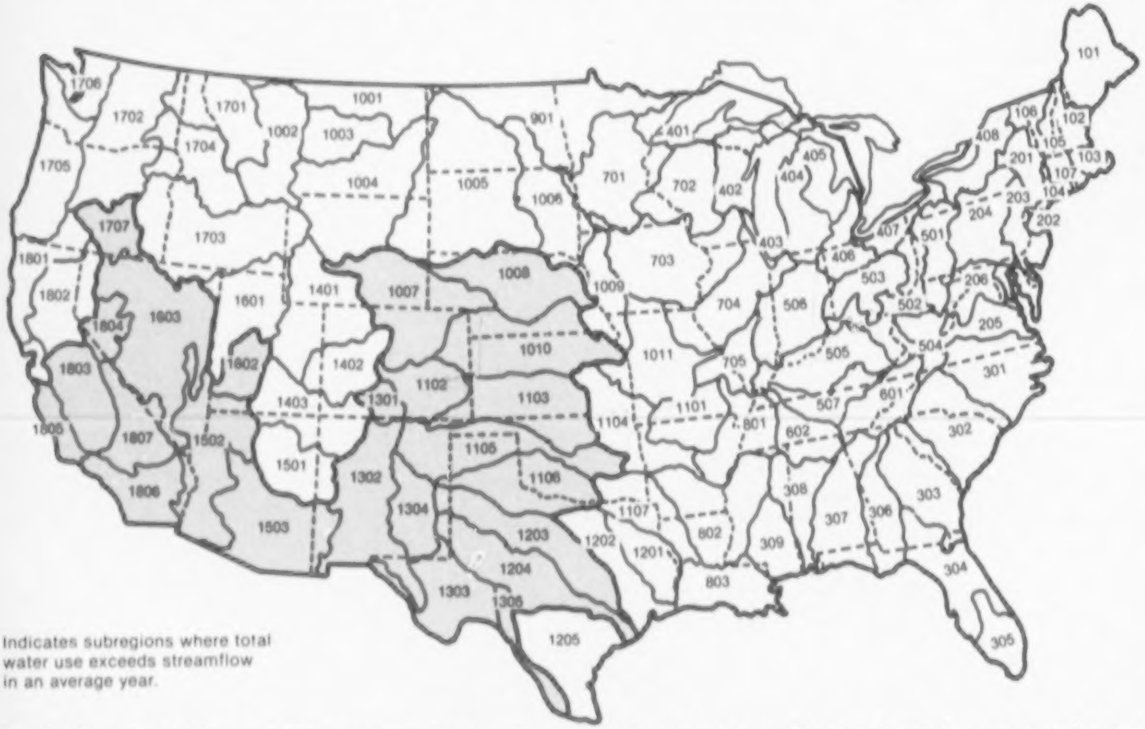
2. south-central California, including the San Joaquin and Owens Valleys, depletion exceeds 75 percent of the annual surface supply;
3. the High Plains of Colorado and west Texas, depletion exceeds 75 percent of annual surface supplies; and
4. much of New Mexico, depletion exceeds 75 percent of annual surface supplies.

A third comparison of water supply and use in the Western United States is contained in the Second National Water Assessment (12). This assessment presents both annual aggregate values of streamflow, total water use (including instream flow requirements), offstream consumption, and ground water mining for the 52 water-resources subregions of the West as well as monthly values for each. In the Second National Assessment, "use" is defined as the total of all offstream consumptive uses plus evaporation losses (from ponds and reservoirs) and net imports of water. "Supply" is defined as the streamflow volume that would occur at the outflow point of each subregion if consumption were eliminated, ground water overdrafting were discontinued, and current water transfer and reservoir practices were continued.

Based on the Second National Water Assessment data for average year conditions, total water use exceeds streamflow in 28 subregions, which account for about 66 percent of the West's irrigated land (fig. 23). In most of the other 24 subregions, there is little difference between streamflow and total water use. Total use is less than 75 percent of streamflow in one subregion, northern California, where there is limited agricultural potential.

In a year of below-average streamflow, the imbalance between supplies and estimated

Figure 23.—Water Resource Subregions Where Total Water Use Exceeds Streamflows in an Average Year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Indicates subregions where total water use exceeds streamflow in an average year.

SOURCE: K. Frederick and J. Hanson, *Water for Western Agriculture* (Washington, D.C.: Resources for the Future, Inc., 1982). (Original source: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 2, pt. II, p. 4.)

total water use is more intense and widespread. Shortfalls are more likely not only because supplies are reduced but also because demand may be higher, especially for irrigation to compensate for reduced precipitation. In a dry year, total water use exceeds streamflow in 48 of the 52 subregions. Four of the exceptions are in the Pacific Northwest region, and the other is in the northernmost subregion of the California region. In eight of the subregions, use is more than twice the dry-year streamflow.

Monthly Estimates of Supply

The use of annual aggregates to determine the water-supply/use patterns of the Western United States often obscures the seasonal nature of many of the shortages that characterize the area. A more reasonable indicator of adequacy would relate water supplies to water needs of humans, animals, and plants during periods of maximum need. Currently, the shortest period for which data are readily available is 1 month. While this is longer than most living organisms can survive without water, it approximates more closely a realistic indicator of water-supply adequacy. An inspection of the Second National Water Assessment data suggests that there are at least three major water-supply/use patterns in the Western United States. These are subregions where: 1) streamflow exceeds offstream uses during every month of the year; 2) streamflow exceeds offstream uses during summer months only, when irrigation withdrawals reach their peak; and 3) streamflow is exceeded by offstream uses during every month of the year.

The Second National Water Assessment found that in 26 of the 52 water-resources subregions of the Western United States, offstream water use exceeded 90 percent of the average monthly supply during at least 1 month each summer (table 16). These subregions are generally located in the areas also identified by USGS sources (1,4) as experiencing water-supply problems. Those areas experiencing at least 1 month of a water-supply deficit during each summer are southern California; the Great Basin; portions of Arizona, New Mexico, Colorado, Nebraska, Kansas, Texas; and the Snake River Plain in southern Idaho.

Consumptive Uses of Surface Water

Consumptive uses of water account for more than the amount being renewed on an annual basis in approximately 40 percent of the water-resources subregions of the Western United States during at least some portion of each year. For much of the Western United States, August is the month of maximum offstream consumptive use. In August, generally, streamflow volumes have diminished significantly from the peak flows of springtime snowmelt. Based on August values of offstream consumption and total streamflow taken from the Second National Water Assessment (12), figure 24 shows that for all of the water-resources regions of the West (excluding the Pacific Northwest), consumption of water is estimated to be about 90 percent of total streamflow during the month of August and goes as high as 395 percent of streamflow in the Brazos River subregion in Texas (12).* Water consumption of many of the subregions of the West actually exceeds 90 percent of streamflow during more than 1 month of each year (see table 16). This suggests that there is currently no excess surface water during August in the Western United States, since even in the Pacific Northwest water that is not used offstream is required for instream hydroelectric generation. In some areas, no excess surface water exists during other months as well. A variable percentage of this water consumption is based on reuse of surface waters and ground water withdrawals depending on the water-resources region. If it is assumed that ground water withdrawal is not sustainable because of "mining" and rising energy costs, current patterns of Western water consumption and use are probably not sustainable.

The monthly patterns of water supply and offstream use for several selected subregions

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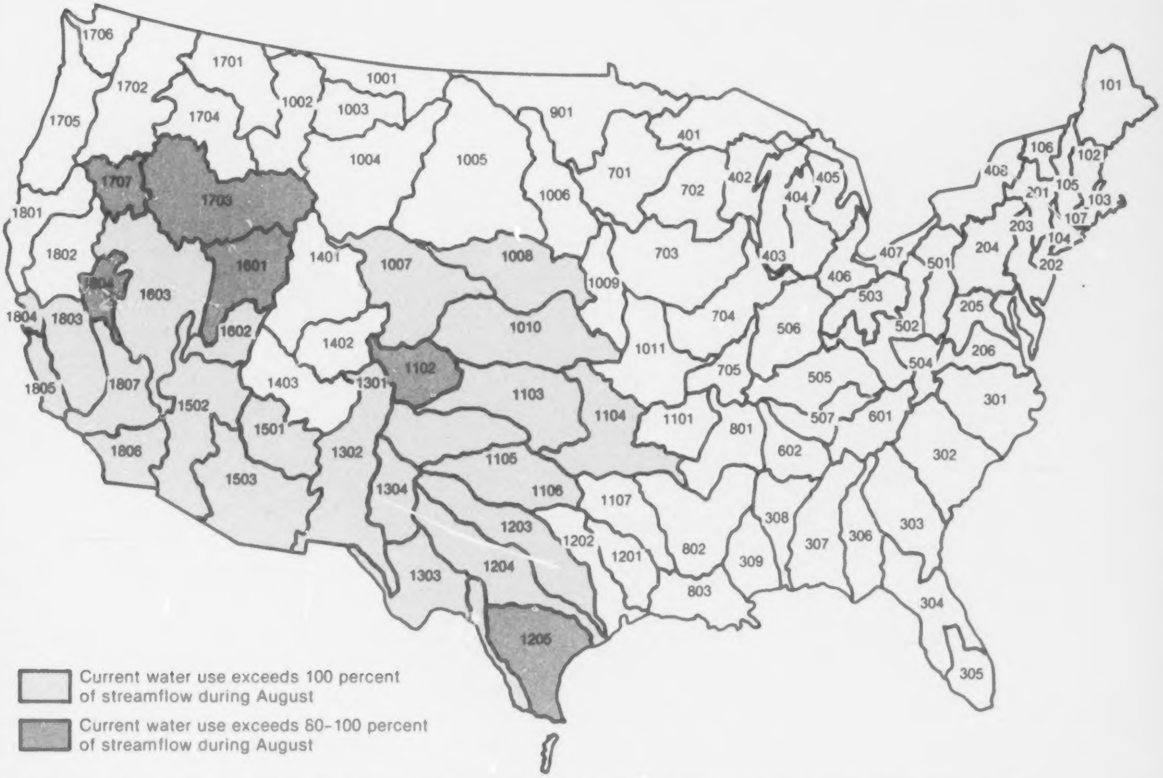
*Total streamflow is defined as a "computed flow that includes effects of consumption, water transfers and evaporation from manmade reservoirs, but not ground water overdraft.

Table 16.—Western Water Resource Subregions Where Offstream Use Exceeds Total Streamflow

Region number	Subregion number	Name	Months during which offstream use exceeds 90% of total streamflow
10		MISSOURI:	
	01	Missouri-Milk-Saskatchewan	—
	02	Missouri-Marias	—
	03	Missouri-Musselshell	—
	04	Yellowstone	—
	05	Western Dakotas	—
	06	Eastern Dakotas	—
	07	North and South Platte	June-September
	08	Niobrara-Platte-Loup	July-September
	09	Middle Missouri	—
	10	Kansas	July-August
	11	Lower Missouri	—
11		ARKANSAS-WHITE-RED:	
	01	Upper White	—
	02	Upper Arkansas	June-July
	03	Arkansas-Cimmaron	July-August
	04	Lower Arkansas	August
	05	Canadian	July-September
	06	Red-Washita	July-September
	07	Red-Sulphur	—
12		TEXAS-GULF:	
	01	Sabine-Neches	—
	02	Trinity-Galveston Bay	—
	03	Brazos	July-September
	04	Colorado (Texas)	June-September
	05	Nueces-Texas Coastal	—
13		RIO GRANDE:	
	01	Rio Grande Headwaters	July-August
	02	Middle Rio Grande	June-October
	03	Rio Grande-Pecos	March-September
	04	Upper Pecos	April-September
	05	Lower Rio Grande	March-August
14		UPPER COLORADO:	
	01	Green-White-Yampa	—
	02	Colorado-Gunnison	—
	03	Colorado-San Juan	—
15		LOWER COLORADO:	
	01	Little Colorado	—
	02	Lower Colorado Main Stem	March-October
	03	Gila	January-December
16		GREAT BASIN:	
	01	Bear-Great Salt Lake	July-August
	02	Sevier Lake	June-September
	03	Humboldt-Tonopah Desert	February-December
	04	Central Lahontan	August
17		COLUMBIA:	
	01	Clark Fork-Kootenai	—
	02	Upper/Middle Columbia	—
	03	Upper/Central Snake	—
	04	Lower Snake	—
	05	Coast-Lower Columbia	—
	06	Puget Sound	—
	07	Oregon Closed Basin	—
18		CALIFORNIA:	
	01	Klamath-North Coastal	—
	02	Sacramento-Lahontan	—
	03	San Joaquin-Tulare	June-October
	04	San Francisco Bay	July-August
	05	Central California Coast	June-September
	06	Southern California	April-November
	07	Lahontan-South	April, July-September

SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 3, app. III, table III-5.

Figure 24.—Ratio of Offstream Consumptive Use to Streamflow During August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□ Current water use exceeds 100 percent of streamflow during August
▨ Current water use exceeds 80–100 percent of streamflow during August

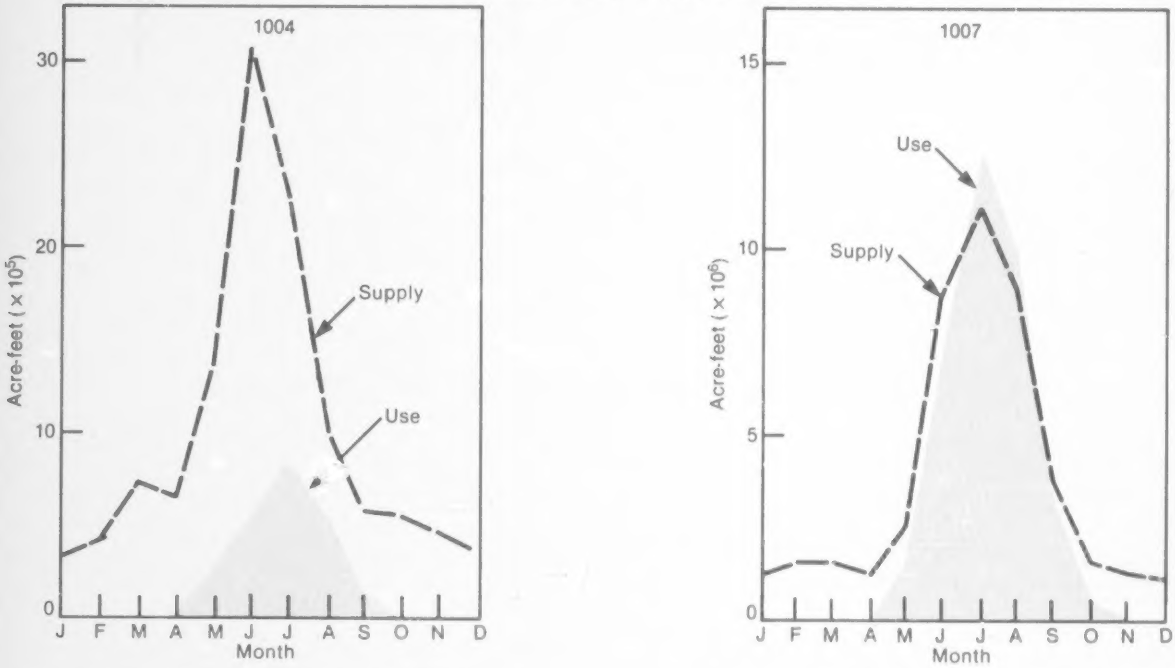
SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978).

in the Western United States are shown in figure 25A, B, and C. These rivers are, respectively:

1. the Yellowstone, a tributary to the Missouri, which has its headwaters in the northern Rocky Mountains;
2. the North and South Platte Rivers, which originate in the Colorado Rocky Mountains and flow eastward through Nebraska to enter the Missouri River; and
3. the Gila River, which drains the southwestern portion of Arizona and includes the metropolitan areas of Tucson and Phoenix within its watershed.

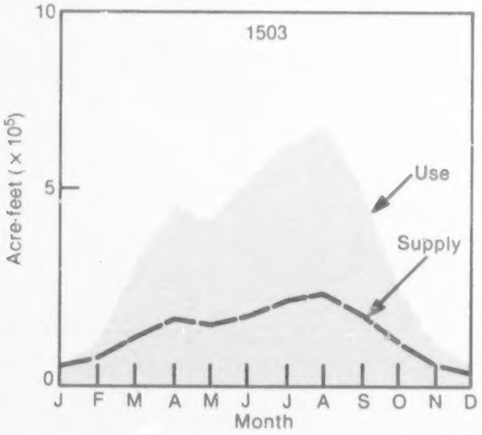
The monthly supply/demand relationships for the Yellowstone River in southwestern Montana are typical of many of the rivers of the Pacific Northwest and northern Rocky Mountains, where water supplies normally exceed withdrawals during all months of the year. For the North and South Platte Rivers in Colorado, Wyoming, and Nebraska, supply exceeds withdrawal only during the winter months. During the irrigation season, from April through August, offstream demand exceeds the supply available from these rivers during each month. The deficit is made up by pumping ground water. This pattern is typical for a majority of the water-resources subregions of the Western United States. The most extreme imbalance between supply and offstream demand is represented by the Gila River, which is characteristic of those in the Southwestern tier of States. Here, offstream demand exceeds supply during every month of the year, a situation made possible only by the reuse of surface water supplies and by extensive ground water "mining."

Figure 25.—Monthly Relationship Between Water Supply and Use for Three Western Rivers



A. The Yellowstone River, a tributary to the Missouri River. This pattern is typical of many in the northwestern portion of the Western United States.

B. The North and South Platte Rivers, tributaries to the Missouri River in the central portion of the Western United States. Use of water in this subregion exceeds supply during a portion of each year. This deficit is made up by pumping ground water.



C. The Gila River in Arizona. Water use exceeds the renewable supply during every month of the year in this river basin. This is made possible only by the extensive mining of ground water.

SOURCE: Office of Technology Assessment, 1982, from U.S. Water Resources Council, 1978.

Offstream demand in excess of surface water supply in the southwestern United States has become a difficult social and economic problem. An extensive social infrastructure has developed in that region based largely on investments that depend on a reliable water supply. In these regions, surface supplies often do not meet demands and ground water must be tapped. From a hydrologic point of view, ground water use in excess of ground-water recharge cannot be sustained into the future, either because of declining volumes of water in the aquifers of the region or increasing pumping costs to extract the water. These factors are contributing to shifts in water-use patterns in the Southwestern United States. (See app. B for further graphics on variability among the water resource regions in spatial and temporal availability of water and in the use of that water.)

Nonconsumptive Uses of Surface Water

A number of nonconsumptive instream uses are as important as consumptive uses but are not often generally considered in determining the supply/use relationship for an area. These are instream requirements for habitat maintenance and waste assimilation, hydroelectric generation, recreation, and the maintenance of commercial fisheries.

Instream uses, " . . . that amount of water flowing through a natural stream channel needed to sustain the instream values at an acceptable level" (12), are particularly difficult to define or quantify. The first attempt to accomplish this was made by the Second National Water Assessment, largely based on minimum streamflow levels required for maintenance of fish and wildlife populations and for navigation, where applicable.

An example of the economic and social desirability of maintaining sufficient instream flow for the support of fish habitat involves the salmon fishing industry of the Pacific States of Washington, Oregon, and northern California. The anadromous (primarily salmon) fish runs of the rivers draining into the sea have national as well as regional importance because they support a commercial fishery, an extensive sports fishery, and an Indian fishery. Damage to this fishery, either by a diminution of instream flows or by undesirable water-quality changes, will have both serious economic and social effects.

Other instream uses also exist that have a direct impact on human activity. An important instream flow use involves waste assimilation and dilution. It is common practice to discharge municipal and industrial wastes into streams with less than complete, or tertiary, treatment (3). Approximately 50 percent of the water used in irrigation returns to the river degraded in quality. Without some minimum level of streamflow, the water quality of return flows will become, in effect, the water quality of the stream. While this will have an effect on fish and wildlife, it also will mean that the water will require extensive and expensive treatment before being suitable for human domestic use.

A third instream use in a number of the water-resources regions of the Western United States involves hydroelectric generation. This use requires that water be "spilled" from a reservoir. If this spillage is to be consistent with the energy demands of the region supplied, reservoir water levels cannot be allowed to fall below some minimum level. If an optimum reservoir level is to be maintained, the spillage must be approximately equal to the amount of water flowing into the upstream end of the reservoir. In the case of the Pacific Northwest Water Resources Region, for example, present patterns of hydroelectric generation require that a monthly average of 140 million acre-ft of water (1.7 billion acre-ft/yr, or more than 12 times the annual flow of the Columbia River) be discharged from the reservoirs of the region to generate the energy being produced there. Without cumulative inflows to these reservoirs of 140 million acre-ft/month, hydroelectric generation must decrease. Thus, this instream use requires a certain volume of water with relatively little room for equivocation. Other uses such as irrigated agriculture, which might require reservoir water, would be detrimental to the hydroelectric use at the point that agricultural demands cause reservoir drawdown and decreased power generation.

Fourth, outdoor recreation activities, while somewhat more difficult to quantify, are important instream uses. According to the Second National Water Assessment, in 1975 there were 592 million water-related outdoor recreation activity "occasions"* in the 17 Western States. On a per-capita basis, this is 11.8 occasions per capita in those States compared with a per capita average of 8.4 occasions in the Eastern United States. Most of the water-related recreational activities in the water-short Western United States center on reservoirs and the free-flowing streams of the region. In both cases, some minimum level of instream flow is required to maintain a reservoir pool level suitable for recreational purposes. A minimum instream flow is necessary specifically to maintain flows during late summer in unregulated streams and to maintain recreational activities below dams on regulated streams.

There are no simple measures of instream flow requirements. To a certain extent, these must reflect the current level of development within a given river basin or along a given stream reach. Water use has already exceeded average annual streamflow in the Southwestern and Great Plains subregions of the Western United States. For these areas, adding another use in the form of instream flow requirements is largely academic.

The issue of instream uses and their priority was raised but not resolved in the Second National Water Assessment. An acceptable definition and quantification of these important uses should be of the highest priority for economic, social, and environmental reasons. Because these uses have national as well as regional and local significance, this area needs national as well as regional and local attention (see also ch. V).

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*Participation by a person 12 years or older in a specific activity without regard to the duration of the activity.

FUTURE ENERGY DEMANDS FOR WESTERN WATER

Water availability is commonly noted as one of the key factors for the successful development of Western energy resources. Some areas of the northern Great Plains and the Rocky Mountain region already are experiencing economic activity as the result of energy development. Surface waters from both the Upper Colorado River Basin and Upper Missouri River Basin, as well as ground waters in these areas, have been described in a number of studies for purposes of water availability for Western energy development.*

Water requirements of energy facilities vary considerably. For example, coal-fired electric power generation requires more water than synthetic fuel technologies and more water than slurry pipelines to produce an equivalent amount of energy. High-Btu coal gasification consumes more water than either coal liquefaction or in situ oil shale production, but less than some oil-shale conversion methods. Water requirements for shipping coal by slurry pipelines are less than for some conversion facilities.

Projections of actual water demand from Western energy development are difficult and depend on numerous assumptions about Western law, needs of existing users, economic value of the water to be used, the specific site and time of development, and the technology used. Studies on individual energy resources have concluded that sufficient quantities of suitable water may be physically available or could legally be made available for certain kinds of energy development. The quality of water required for some energy uses may be lower than that required for agriculture.

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*See previous OTA reports on: *Increased Automobile Fuel Efficiency and Synthetic Fuels: Alternatives for Reducing Oil Imports*, OTA-E-186, September 1982; *An Assessment of Oil Shale Technologies*, OTA-M-118, June 1980; *The Direct Use of Coal: Prospects and Problems of Production and Combustion*, OTA-E-86, April 1979; and *A Technology Assessment of Coal Slurry Pipelines*, OTA-E-60, March 1978. Also see Science and Public Policy Program, University of Oklahoma, *Energy From the West: A Technology Assessment of Western Energy Resource Development*, 1981, University of Oklahoma Press.

No definitive estimate of the cumulative effects of Western energy development for agriculture is available, however. The difficulty with providing such an estimate is due, in part, to complex and dynamic legal, institutional, political, and economic issues involved. Moreover, data on water availability, current uses, and future demands are incomplete. The impacts of water demand for energy hinge on the quality of water required and future local, State, and Federal roles in programs to make water available for energy development. International activities also will influence the Western energy industry. The energy-specific studies generally recognize that on a site-specific basis, some Western agricultural areas could experience significant impacts from increased water use for energy.

CONCLUSIONS

Both the spatial and temporal availability of water for agricultural uses in the Western United States are related to variations in the components of the hydrologic cycle. It should be recognized that the use of a technology to produce a change in any single component of the hydrologic cycle to create additional water or water savings will inevitably affect other components of the cycle. A detailed analysis of the existing hydrologic regime at the site of technological modification will help to determine the extent to which that modification will affect the desired change (e.g., in increased surface runoff, decreased evapotranspiration, and increased soil-water storage). It will also help to define possible adverse impacts on other components of the cycle.

Evaluating the potential of a given technology for either producing additional water or conserving supplies will be difficult unless the quantities of water now involved are defined more accurately. Both the reliability and availability of water-resources data present problems for site-specific hydrologic analysis. Estimates of annual streamflow volume now vary by as much as several hundred percent, depending on the river basin and the source of the estimate. Additional cooperation and coordination among the involved Federal and State agencies would help to resolve water-data problems and discrepancies. Consideration should be given to using a lead agency concept for various data-related activities.

It is inevitable that both short- and long-term fluctuations in climate affecting water availability in the Western United States will continue in the future. Short-term variations in water supply lasting a single season or year have traditionally been a factor in planning and management of the water resources of the region. Changes in the water supply associated with long-term changes in the climate are less commonly considered in either planning or management. The past several decades have been particularly favorable for agricultural development. It must be assumed that present levels of agricultural production are at least partly the result of this. Short-term fluctuations in water supply can be accommodated in management and planning schemes by a statistical analysis of trends in the recent past. However, because there is no reliable method for predicting the nature of long-term trends, water use and planning over the long-term should tend toward conservative estimates of future availability.

The most important source of renewable surface water supplies in the Western United States is the mountain snowpack. This snowpack accumulates during the winter months in both the mountains bordering the Pacific Ocean and the Rocky Mountains in the interior. When it melts in the spring and summer months, it supplies an estimated 70 to 100 percent (depending on location) of the total annual surface runoff for all river basins except the Texas-Gulf region. Traditionally, the approach to the study of water resources in the Western United States has been one that emphasized problems related to meeting demand rather than those associated with the sources of supply.

Relatively little research attention has been given to the snowpack, either in terms of the spatial and temporal variations of volume of water stored each year or the rate at which surface runoff is produced during the melt seasons. Technologies such as weather modification and streamflow forecasting to improve reservoir management would benefit considerably from an increased understanding of the snowpack as the dominant source of the renewable surface water supplies. The snow survey program of the USDA Soil Conservation Service has produced a valuable data base that would greatly facilitate this research.

Based on the available estimates of water supply and use, almost half of the Western United States is experiencing water-supply problems in relation to demand. In much of the Southwest and southern High Plains, the total available surface supply is used in some way annually, and ground water is being withdrawn faster than its recharge rate in order to sustain the levels of use that have developed. Ground water mining can only be considered a short-term solution to water-supply problems, since diminishing reserves and increasing energy costs may gradually make the pumping of ground water prohibitively expensive. Where water supply is not entirely consumed, competing nonconsumptive uses, such as instream flow requirements or hydroelectric generation, are increasingly creating scheduling conflicts for offstream uses. Water-quality problems may prove to be an even more critical factor affecting patterns of future Western water use.

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IV

"Pollutions" Water Quality

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Chapter IV

Water Quality

Water-quality deterioration in the Western United States would have significant impacts on water use. Although agriculture is the primary user of water in the region, water-quality problems are associated with all uses.

This chapter presents an overview of two aspects of water quality of the Western United States: 1) the impacts that water quality has on agriculture and 2) the impacts that agriculture has on water quality. While the chapter is not an exhaustive consideration of all the water-quality implications for water supply and use in the Western United States, it does illustrate the broad nature of the problem and some of the more salient public health implications.

The discussions of this problem in the literature, on which this chapter is based, are fragmentary, and it is apparent that legitimate differences of opinion exist concerning the seriousness of the problem. Water planners and managers must be aware of these different interpretations but must also understand that, at least locally, water pollutants and their associated health problems have been detected in the region. With the increasing water usage indicated by present trends, these pollution and health problems can only worsen without concerted action on the local, State, and Federal level.

WATER QUALITY IN ARID AND SEMIARID REGIONS

Water quality defines the physical, chemical, and biological attributes that affect the suitability of water for agricultural, industrial, and domestic uses as well as for recreation and wildlife habitat. These attributes are closely linked to the physical availability of water, the extent to which the available resources are used, and the nature of the water-quality changes that use produces. Water quality is determined both by the nature of the pollutant and the concentration of that pollutant in the water.

No water problems are unique to the arid and semiarid portions of the Western United States. The more limited amount of water available in this environment, however, has the potential to increase the severity of any that do exist. For example, arid and semiarid environments are commonly characterized by high natural levels of salinity in the soil owing to the imbalance between precipitation and evaporation which decreases natural leaching. The sporadic runoff that characterizes these environments will often contain high concentrations of both suspended and dissolved solids which are added to the perennial river system. It is estimated, for example, that natural sources account for about two-thirds of the total annual dissolved salt carried by the Colorado River. For portions of this river, this represents values that may exceed 1,500 parts per million (ppm) total dissolved solids, or three times the recommended level for municipal drinking water.

The fact that there is less total water available in arid and semiarid environments means that each unit of water must be more fully used, resulting in the development of patterns of reuse in which each unit of water must be used consecutively as it moves through a river system. Thus, water may be withdrawn from the river and partially consumed by irrigation; the return flow may be stored in a reservoir where it will ultimately be used to generate hydroelectric energy; and then, following release, the water may be withdrawn by a municipality for domestic consumption. The return flows from each of these sequential uses have increasing levels of pollutants and may ultimately have little reuse potential without significant treatment (35). While continued reuse of streamflows for irrigation without treatment has become a necessity in many of the water-short areas of the Western United States, the gradual buildup of salts and agricultural chemicals in the soils and in the water itself could ultimately prove to be more detrimental to agriculture and other water users than will increasing water shortages.

Traditionally, the streams, lakes, rivers, and ground water of the Western United States have seemed a convenient and seemingly inexpensive and inexhaustible dumping area for human and animal wastes and residues from industry and municipalities. Many water-quality problems have been identified in the Western United States; most on a site-specific basis, depending on the type of pollutant and the nature of the ground and surface water system into which it is introduced. Experts disagree about the nature or extent of existing water-quality problems and about related public health aspects. Based on available evidence, however, concern is justified.

The kinds and amounts of impurities in water depend on a number of environmental factors, such as source of water and physiographic characteristics of the environment through which the water moves, and on the effects of human activity on water quality. In practice, it is difficult to separate water-quality from water-quantity problems in the Western United States. The development and use of the region's water resources have generally tended to decrease the volume of water in both surface and subsurface sources and to increase the concentration of both natural and human-caused contaminants. The ability of Western water resources to assimilate the increased levels of contaminants that might be produced by urban populations, industrial activities, and use of agricultural chemicals is more limited than in the humid Eastern United States because of lower total volumes of water. Because of the interconnected nature of ground and surface water supplies, contamination of one will eventually affect the quality of the other.

In discussing water quality in relation to agricultural development, two major issues arise. On the one hand, agricultural use requires certain standards of water quality. Under conditions of water scarcity, waste products concentrating in surface or ground water supplies can appreciably diminish the availability of suitable water for agricultural use. On the other hand, agriculture itself contributes waste products to the environment affecting water quality and its suitability for other uses.

THE EFFECTS OF WATER QUALITY ON AGRICULTURE

Technologically, water of any quality can be made suitable for any use. However, to neutralize or remove certain types of pollution from water is prohibitively difficult and expensive. The extent of improvement a water supply will require and the associated costs usually represent the rationale in assessing the comparative worth of alternative supplies.

"Water quality" in agriculture relates primarily to farmstead water supply, livestock, watering, and irrigation. Understanding the significance of a great variety of water constituents regarding tolerance limits for various uses is far from complete. However, the provisional threshold tolerance levels available for many water constituents may serve as guides in evaluating the suitability of water for particular uses. In 1963 the California State Water Resources Control Board published the first "Water Quality Criteria" for various uses, including agriculture (33). In 1968 the Federal Water Pollution Control Administration published "Water Quality Criteria" in which considerable emphasis was given to water-quality requirements in agriculture. In 1976 the Environmental Protection Agency (EPA) contributed "Quality Criteria for Water." In 1977 the

National Research Council of the National Academy of Sciences published "Drinking Water and Health," which summarized the state of knowledge on the effect of various drinking-water constituents on human health.

Domestic Use on Ranches and Farms

The requirements for water quality for domestic use by a human population in an agricultural setting should not be different from requirements for drinking-water quality elsewhere. However, water available on farms and ranches is usually in a raw state, while water in the cities is treated to make it suitable for human consumption. Thus, farm and ranch water must be of such quality that it can be consumed without, or with minimal, treatment. Because water used by individual households in rural areas is not subject to routine quality inspections as are public water supplies in the cities, there is very little information on the quality of drinking water available to rural populations. Some rural drinking-water supplies have become polluted. For example, analysis of water in California during 1979 revealed that some 100 water-supply wells contained trace amounts of DBCP (dibromochloropropane), formerly a widely used pesticide and a suspected carcinogenic compound (47)

Livestock

It is usually accepted that water that is safe for human consumption may be used safely by stock, but that some stock can tolerate water of a somewhat poorer quality. According to Heller (25,26), the maximum concentration of salts that can be tolerated by certain domestic animals is about 15,000 milligrams per liter (mg/l), but this limit is believed to be too high for food-producing animals. The maximum acceptable salinity level for livestock drinking water suggested by EPA (50) was 3,000 mg/l of soluble salts.

In general, the types of pollutants in water that are of potential significance to livestock are mineral salts, organic wastes and algae, microbiological pathogens and parasites, pesticides, herbicides, and radionuclides. Livestock water can be contaminated in many ways, either directly from natural sources or indirectly; e.g., agricultural fertilizers may stimulate algae "bloom" in the water so that it becomes unsuitable for animal watering. Various water pollutants may cause either loss of livestock by death or by reduced reproduction.

Irrigation: Salts and Ions

The quality of water used in irrigation is very important. It is known that water retained in soil (so-called "soil solution") tends with the passage of time to become progressively more saline. This process is believed to be responsible for the failure of many irrigation projects throughout the history of civilizations (7).

Using an inferior quality water for irrigation can affect soil by changing soil structure (permeability and aeration), and plants through the presence of phytotoxic substances in water or through the modification of processes that limit the water uptake by plants. Moreover, some constituents of irrigation water of no particular significance to plants themselves, but significant to animals and humans, can be accumulated by crops.

An evaluation of water suitability for irrigation based solely on water characteristics has limitations because more factors are involved. First, the "soil solution" is usually several times as concentrated as the water applied (in some cases it may be as much as 100 times more concentrated). Second, plants vary widely in their tolerance to salinity (see ch. IX, table 67). Third, soil types, climatic conditions, and irrigation practices and drainage conditions are of importance and vary widely. Well-drained soil can support growth of satisfactory crops even if the water applied to it is not of the best quality. However, poorly drained soils favor buildup of undesirable constituents, even if the constituents are present in rather small quantities in the water.

The characteristics of water most often considered in determining the suitability of water for irrigation use are: 1) the total concentration of salts in water (measured in mg/l or as the specific conductance, in micromhos); 2) the proportion of sodium to calcium and magnesium (often in percent); and 3) boron, chloride, and sulfate content in mg/l (table 17). Each of the characteristics varies relatively independently. Thus, water, adequate in all other respects, may not be suitable for irrigation because of a specific single adverse water-quality factor.

Soils in arid and semiarid regions have specific salt-accumulation problems. Such soils have been formed under limited precipitation conditions and scarce vegetation. Infrequent infiltration by rainwater causes the soils in such areas to be more shallow and saline. In order to maintain a steady state, salt accumulation in the process of irrigation should be balanced by equally effective salt removal, a difficult practice to accomplish. In most cases, salt removal may succeed only in moving the problem downstream to the next point at which water is withdrawn for irrigation application.

The proportion of sodium to other cations* in water is used to indicate the relative activity of sodium ions in exchange reaction with soil. Sodium hazard increases if water has a large concentration of bicarbonate ions. Alkaline water will act to dissolve the organic material in the soil. The effect is known under the general term of "black alkali," referring to the characteristic black-grayish color of the affected soil. Because of these considerations, the RSC* index (residual sodium carbonate) was suggested as an additional criterion for irrigation water. Water containing more than 2.5 mg/l of RSC is probably not suitable for irrigation; with RSC in 2.5 mg/l, water is marginal, and with RSC lower than 1.25 mg/l, water is probably safe (53).

While trace quantities of boron in water are essential for plants as a micronutrient, an excess of this element can cause plant injury. The information on tolerance of plants to boron as well as several other trace elements is presented in table 18.

Irrigation With Wastewater

In conditions of water scarcity, the reuse of wastewater in irrigation has been considered as a possible way to stretch available resources.

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*Positively charged ions.

*RSC $= (CO3^{--} + HCO_{-3}) - (CA^{++} + Mg^{++})$, Ionic content in milliequivalents per liter.

Table 17.—Summary of Classifications of Irrigation Waters

Class	% Na $\frac{Na \times 100}{Na + Ca + Mg + K}$ as meq per liter	Boron, in mg/l	Chlorides in meq/l	Sulfates in meq/l	EC × 10^6 at 25° C Specific conductivity (concentration of ions)	Total salts in mg/l
I	Less than 30-60% (most recent work favors a 60% limit)	Boron recommendation for water of this class is generally accepted as less than 0.5 mg/l; however, tolerant plants will not be injured by 1-1.5 mg/l	Less than 2-5.5	Less than 4-10	Earlier papers suggested limit of about 500, but more recently 1,000 has been accepted	Up to about 700
II	30-75%	0.5-2.0 mg/l although for tolerant plants water with boron up to 3.35 mg/l may be satisfactory	2-16	4-20	500-3,000	350-2,100
III	More than 70-75%	More than 2 mg/l although water with more than 1.0 may be highly unsuitable for sensitive plants	More than 6-16	More than 12-20	More than 2,500-3,000	More than 1,750-2,100

SOURCE: J. E. McKee and H. W. Wolf, *Water Quality Criteria*, California State Water Resources Control Board, 1963.

Table 18.—Trace Element Tolerances for Irrigation Waters

Element	For water used continuously on all soils (mg/l)	For short-term use on fine textured soils only (mg/l)
Aluminum	1.000	20.00
Arsenic	1.000	10.00
Beryllium	0.500	1.00
Boron	0.750	2.00
Cadmium	0.005	0.05
Chromium	5.00	20.00
Cobalt	0.200	10.00
Copper	0.200	5.00
Flourine	(1)	(1)
Iron	(1)	(1)
Lead	5.000	20.00
Lithium	5.000	5.00
Manganese	2.000	20.00
Molybdenum	0.005	0.05
Nickel	0.500	2.00
Selenium	0.050	0.05
Tin	(1)	(1)
Tungsten	(1)	(1)
Vanadium	10.000	10.00
Zinc	5.000	10.00

SOURCE: J. E. McKee and H. W. Wolf, *Water Quality Criteria*, California State Water Resources Control Board, 1963.

However, the safety and desirability of land application of wastes has been a controversial issue. The divergence of opinion in this matter was reflected by participants of the Fourth National Groundwater Quality Symposium in 1978. At this symposium Wright and Rovey (both private sector water engineers) characterized such a practice as beneficial, arguing that "land application of treated wastewater can provide unique opportunities not only for a final high level of waste treatment, but for reasons of nutrients as well." To support this conclusion, the authors presented several examples of land application of treated municipal and industrial wastewater with no detectable impact on ground water quality (57). In agreement, Sheaffer, the president of a company that works with wastewater reuse, suggested that "land treatment systems provide an opportunity to view sewage treatment as an investment in the production of food and fiber." It "provides our nation with a positive program to deal with a negatively perceived material, sewage" (41).

On the other hand, Johnson, chairman of the National Drinking Water Advisory Council and vice president of an environmental engineering company, characterized land application of waste as "an accident waiting to happen." He indicated that research has not been done to give assurance that natural interaction of wastewater and soils will remove to acceptable levels potentially harmful contaminants. He cited several examples where sewage effluents penetrated the ground to the water level. "There is a great deal to be learned," he said, "about the fate and transport of contaminants below the surface; the practices that represent the greatest threat to this national resource; and the economics of alternative ways of disposing of wastes in a manner more protective of the environment." Johnson quoted California State studies in 1976 that concluded that "areas of uncertainties regarding health effects cannot be resolved because basic scientific knowledge is lacking" (29).

A 1979 report by the United Nations World Health Organization (WHO) warned that the application of wastewater to land, whether for agricultural irrigation or as a method of treatment for disposal, poses a possible risk of virus contamination of ground water. The report emphasized that "concern about hazard from viruses caused by this practice has only recently been raised, and available information remains limited." Concentration of enteric viruses in human feces was reported to be as high as 10^5 to 10^8 PFU/g (plaque-forming units per gram) (56). Raw sewage and wastewater usually contain a large number of enteric viruses of human origin. Although sewage treatments reduce virus contamination to varying extents, significant numbers of viruses survive treatment.

Because viruses in wastewater that is applied to land can survive in the environment for a considerable period of time (27), the application of inadequately treated effluents and sludge to land poses the risk of potential public health problems. According to the 1979 WHO report, deposition of significant concentrations of viruses on the soil might be a health hazard via:

- direct virus infection of farmworkers and their contacts,
- virus contamination of crops destined for human consumption,

- virus contamination of the drinking-water source (surface contamination by runoff or ground water contamination by percolation),
- dissemination of viruses by insect vectors or animals in contact with contaminated soil, and
- virus dissemination by the air when sprinkler irrigation is used.

An improved understanding of factors that influence virus retention and inactivation in soil and of factors controlling virus migration through soil is critical in managing wastewater land-treatment systems. According to studies by Gerba, et al. (19), virus retention in soil is believed to occur mainly by the mechanism of adsorption,* which, in turn, is controlled by a number of variables; e.g., soil composition and ionic content, pH, moisture content, temperature, rates of wastewater application, strength of sewage (19,27). Moreover, adsorptive behavior of viruses and their survival were also demonstrated to be strongly type- and strain-dependent. Hurst, et al. (27), reporting this observation in 1980, stated:

> The fact that [adsorptive capacity] significantly affected virus survival is of great importance. This finding indicates a dilemma insofar as virus inactivation during land treatments is concerned. On one hand, concern for public health would, of necessity, require that land treatment sites be developed on soils with high virus adsorptive capacity. This is required to minimize the possibility of viruses applied to soil reaching groundwater. On the other hand, virus survival is likely to be greatest in those soils that would be most effective in preventing groundwater contamination.

Heat

Water-temperature increases can result from industrial water use and from water impoundment. Such increases have a direct effect on the efficiency of water as a coolant and an indirect influence on aquatic life and on water chemistry. A change in water temperatures, by itself, has little effect on the agricultural uses of water. However, changes in water temperature may produce associated water-quality changes which will render the water less desirable for a variety of agricultural uses. For example, an increased water temperature increases the solubility of all substances including those that may be harmful to agriculture. With higher water temperatures the dissolved oxygen content is lowered, increasing the possibility of eutrophication, including the production of anaerobic decomposition products and increased algae growth, when sufficient nutrients are present. Pathogenic organisms will survive for longer periods of time at higher water temperatures, thus increasing the risk of disease transmission both to and from agricultural areas.

Radioactive Substances

The possibility of the uptake and translocation by plants of the radioactive material from fallout—in particular strontium, cesium, barium, and iodine—has been identified in some literature (33). Radioactive material can be picked up by rivers as they cross areas of uranium mining (7). Uranium mining exists in several States—e.g., Utah, New Mexico, Arizona, and Texas. Some streams used for irrigation purposes either cross through uranium districts or originate within the uranium districts (9,55). Ground water can also be contaminated in the process of uranium exploration.

THE EFFECTS OF AGRICULTURE ON WATER QUALITY

Agriculture contributes its share of water pollution, both from point and nonpoint sources.* The impact of agricultural wastes such as sediments, dissolved salts, and bacteria on water quality has been given comparatively little attention until recently (14,51). Within the past several decades the use of agricultural chemicals (pesticides and fertilizers) has become widespread in the West, and a sizable feedlot industry has been created with massive concentrations of livestock, poultry, and the resultant waste products. These kinds of activities raise serious concerns about Western water quality.

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*Adherence of one particle, ion, or molecule to the surface of another.

*Point pollution comes from sources that can be pinpointed; nonpoint pollution comes from diffuse sources. See app. E.

Suspended Sediments

The greatest mass of waste resulting from agricultural activity in terms of quantity is probably the material eroded from cultivated land. The total quantity of sediment production in the United States is appreciable, estimated to be as much as 6.4 billion tons per year (11). Waterborne sediments are solid particles of various sizes composed of inorganic and organic materials eroded from soil and rocks, products of plant and animal decomposition, and debris of human activity.

Much sediment and erosion results from poor agricultural management practices according to a report prepared by the Department of Agronomy at Cornell University (14). The problem is magnified by numerous individual farmers who, either for lack of knowledge, carelessness, or economic necessity, do not practice proper methods of erosion control, manure application, or agricultural chemical application.

Although there is no evidence that common suspended sediments or solids affect health directly, they can affect health indirectly. Specifically, clays are very adsorptive and can provide a transport mechanism for viruses, bacteria, and various toxic substances into drinking-water supplies. Pesticides and fertilizers bind to soil particles and are later mobilized by erosion and transported by runoff. Paraquat and Diquat (herbicides) and phosphorus (fertilizer) are examples of chemicals that can be transported by clay particles (36). Viruses and bacteria tend to concentrate in the bottom sediments of lakes, rivers, and estuaries (22,32,36).

Some organic pollutants that do not adsorb readily on pure clays adsorb on clay-organic complexes in the sediments. Water treatment is usually capable of removing most of the suspended material; in cases when it is not, such material may be ingested. Pollutants bound to clay particles may be released into the water or into the digestive tract of humans and animals.

Other problems commonly reported in association with waterborne sediments come from agriculture. These include impairment of drainage, reduction of reservoir storage capacity, and increased need for dredging of water-development projects. Waterborne sediments increase costs of water clarification for industrial use and potable water delivery. Coarse sediments cause abrasion of turbine blades in power-generation facilities and clogging of injection wells. Economic losses to commercial fisheries can result from the effects of sediment on spawning grounds.

Plant Nutrients and Fertilizers

Nutrient transport from cultivated land and feedlots is among the most frequent problems associated with agricultural activity. While elements such as phosphorus and nitrogen are essential nutrients for any terrestrial or aquatic ecosystem, the overenrichment of water bodies with these same chemicals may bring about an uncontrolled algae "bloom" and excessive growth of aquatic plants. This growth leads to problems in waterways and canals and interferes with water recreation and other beneficial uses of water. Decaying water plants reduce the quality and length of the useful life of farm ponds, lakes, and reservoirs.

Phosphorus

According to some experts, phosphorus may be one of the most limiting nutrients in aquatic habitats. Agricultural sources of phosphorus include fertilizer and runoff from animal feedlots. Phosphorus, unlike nitrogen, does not readily leach out of soil. Soil can hold large quantities of this nutrient in a fixed state. Erosion and sediment transport is the primary way in which phosphorus is introduced into water bodies. Phosphorus commonly is present in greater concentration in the bottom sediments of a water body than in solution.

Some research has shown that algae "bloom" can exist at phosphorus concentrations in water as low as 0.1 ppm. However, such algae could not sustain itself for long at this initial concentration unless phosphorus were resupplied at least 15 times throughout the growing season (14). It is believed that the amounts of phosphorus moving off the land as fertilizer may not be sufficient to support the algae "bloom" experienced in farm ponds, lakes, and reservoirs. Runoff from barnyards, animal feedlots, and domestic sewage also contribute phosphorus to water.

Nitrogen

A second nutrient and potential water pollutant is nitrogen. Nitrate contamination is likely to be of importance where rural water supplies are concerned. Major sources of nitrogen-containing wastes are drainage from animal feedlots, irrigation reuse water, wastewater from municipalities and industries, solid waste dumps, and septic tanks. An important nonpoint source is runoff from fertilized land (chemical or manure) (36). It has also been suggested that some nitrates in ground water are of a natural origin—i.e, indigenous to some geological deposits—e.g., tertiary and quartenary sands (18). The origin of excessive nitrates in shallow wells is a subject of debate. Several recent reports from the United States and England have suggested trends of increased nitrates in water attributed principally to the increasing use of organic and inorganic fertilizers in areas of arable farming and to changes in methods of farming (16,24,58).

IMPACTS ON HUMAN HEALTH

An excessive intake of nitrate or nitrite leads to the development of methemoglobinemia.* The effect has been well documented in humans, and a similar effect has been observed in animals exposed to high doses of these chemicals (36).

Evidence implicating nitrate, nitrite, and N-nitroso compounds in the development of cancer in humans is circumstantial. Several epidemiological studies of certain geographical/nationality groups have provided data that are consistent with the hypothesis that exposure of humans to high levels of nitrate and nitrite may be associated with an increased incidence of cancers of the stomach and esophagus (see, e.g., 2,13,59). In none of these studies was there a direct attempt to investigate actual exposures of nitrate, nitrite, or N-nitroso in individuals who developed cancer, however. In most of the studies, several other plausible causative agents were also identified (36).

Many N-nitroso compounds are clearly carcinogenic in many species of laboratory animals, suggesting that they should be considered as possible human carcinogens. However, the value of these tests in making predictions of the nature or extent of risk to humans is unknown (36). It has been recommended that exposure to the precursors of N-nitroso compounds—especially nitrate and nitrite—and to preformed N-nitroso compounds be reduced (36). A thorough discussion of pathology associated with N-nitroso compounds is available in a publication of the International Agency for Research on Cancer (28).

IMPACTS ON ANIMALS

Cattle, sheep, goats, horses, swine, and birds are farm animals susceptible to nitrate poisoning which occurs when nitrate is ingested faster than it can be reduced and incorporated into proteins. In such a situation, nitrite is then absorbed into blood where it converts hemoglobin into methemoglobin. This reaction reduces the oxygen-carrying capacity of blood, and the animal then experiences oxygen deprivation and may die by asphyxiation. Other consequences are spontaneous abortion, reduced production of milk, and signs of vitamin A deprivation.

Dissolved Salts

A favorable mineral salt balance in the soil is essential for human survival and for successful functioning of agriculture. Water that evaporates from the soil surface or is transpired by the plants is salt-free, and thus salt residue tends to be left behind not only in the soil but also in any water flowing through the field. As a result, the irrigation return flow usually has a much higher salt burden than does the incoming water.

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*Presence of methemoglobin (a chemically altered hemoglobin which does not combine with oxygen) in the blood results in cyanosis (bluish discoloration due to deficient oxygenation of the blood).

Wadleigh (51) has suggested that irrigation does not actually produce waste in the form of dissolved salts nor add much to this salt burden by the application of chemical fertilizers. He suggests that irrigation transfers the salt loads in a more concentrated form into return flows from irrigation. The increased salt burden of irrigation drainage water renders the water of receiving streams and rivers less suitable for downstream users. Progressively higher salt concentrations of irrigation return flows may render receiving waters unfit as a potable water supply or for other uses.

Sodium is one of the salts that may build up in relatively high proportions in irrigation return flow as water on the field evaporates. The impact of sodium excess on nonagricultural uses of water—in particular, water designated for human consumption—has not received widespread recognition. Sodium is a life-essential element, and the amount that can be tolerated by healthy people is believed to be considerable. For people suffering from some illnesses, however, excessive intake of sodium (salt) is undesirable, and might be harmful. These illnesses include congestive heart failure, hypertension, liver cirrhosis, renal disorders, adrenal hyperfunction, and possibly certain complications of pregnancy.

The U.S. Public Health Service limits the total dissolved solids in water destined for human consumption to 500 mg/l and the chloride content to 250 mg/l. A report of the National Research Council (38) indicates that over 6 million people in the United States are on physician-prescribed salt-restricting diets. When drinking water contains sodium in a concentration greater than 20 mg/l, compliance with restricted diets of 1 g or less daily becomes difficult. In view of this fact, the American Heart Association (1) recommended that the amount of sodium in water for use in salt-limiting diets shall not be in excess of 20 mg/l. White, et al. (52), found that many municipal water supplies are unsuitable for patients on severely restricted sodium-salt diets. Drinking water containing sufficient sodium to interfere with the aims of salt-limiting diets had been reported by Krishnaswami (31), Cech, et al. (10), and Gonzales, et al. (21).

Animal and Other Organic Wastes

The tendency in animal husbandry toward huge confinement-type operations with feedlots containing thousands of cattle and hogs and hundreds of thousands of poultry creates massive and serious waste problems. It has been estimated that domestic animals produce over 1 billion tons of fecal material a year and animal liquid sewage amounts annually to 400 million tons (51). Together with other wastes, such as animal carcasses, the total amount of waste products from animal husbandry is estimated to be around 2 billion tons per year; about half of this is generated in concentrated confinement-type operations.

One of the problems in coping with animal waste stems from its high biochemical-oxygen demand (BOD), the amount of oxygen necessary to decompose organic material present in water. A feedlot of 10,000 cattle may produce a sewage-disposal problem equal to that of a city of more than 160,000 people. The major differences are that sewage from a city of this size would be diluted in about 8 million gallons of water, while feedlot wastes are undiluted. Also, most cities are served by some form of sewage treatment facilities, while often feedlots are not. Table 19 provides estimated population equivalents of the fecal production by animals expressed in terms of BOD.

Other sectors of agricultural manufacturing are also known to contribute wastes with high BOD. These include fruit canning; sugar refining, fermenting, and distillation; animal slaughterhouses; meat processing; dairy cleaning; wool processing; and cotton manufacturing (51). Also, runoff of decaying products from

Table 19.—Population Equivalent of the Fecal Production by Animals in Terms of Biochemical Oxygen Demand (BOD)

Biotype	Fecal G./cap./day	Relative BOD per unit of waste (lb)	Population equivalent
Man	150	1.00	1.00
Horse	16,000	0.105	11.30
Cow	23,600	0.105	16.40
Sheep	1,130	0.325	2.45
Hog	2,700	0.105	1.90
Hen	182	0.115	0.14

SOURCE: E. H. Wadleigh, *Wastes in Relation to Agriculture and Forestry*, USDA Miscellaneous Publication No. 1065, 1968.

plant residues on farms and ranches contributes organic materials to the receiving water bodies.

Oxygen-demanding wastes act to impair the quality of the receiving water. Common effects are depletion of oxygen in bacterial decomposition of organic wastes, changes of conditions in the water from aerobic to anaerobic (putrid), characteristic foul odor, and algae "bloom."

Water-Treatment Problems

Undesirable effects on water supplies from the overload of oxygen-demanding organic wastes is comparatively well recognized. Recently, however, other problems related to high organic content in receiving water have been identified. When such water is subjected to chlorination at water-treatment plants, some exotic compounds are synthesized by chlorine interactions with organics (4,40). The compounds so formed are collectively known as trihalomethanes (chloroform, bromoform, bromodichloromethane, and dibromochloromethane). Some of these compounds are recognized animal carcinogens and suspected human carcinogens.

The cancer-causing potential of one of these trihalomethanes, chloroform, was suggested as early as 1945 by Eschenbrenner from studies with mice. These results were confirmed later by the National Cancer Institute (37) which reported that chloroform induces certain kinds of tumors in male and female rats. The carcinogenic properties of a related compound, carbon tetrachloride, were demonstrated also with rats and mice, and a possible accumulation of this compound in blood plasma was reported by Dowty and associates (15).

The mutagenic properties of two other trihalomethanes (bromoform and dibromochloromethane) were demonstrated by Simmon and Poole (43) and by Theiss, et al. (46). Brungs (5), in assessing the effect of chlorination of wastewater effluents on aquatic life, concluded that the end-product compounds created after chlorination of wastewater are often entirely different from the original material and are more toxic.

In 1974, EPA undertook the National Organic Reconnaissance Survey that included 80 U.S. cities (45). Chloroform was detected in the drinking water of 95 percent of those cities. It was concluded that trihalomethanes were probably present in almost all drinking water disinfected with chlorine. They are more likely to occur in higher concentrations when surface water is the source of raw water because the organic content of raw water is high, when prechlorination is used, and when the dose of chlorine required to disinfect water is high.

Several epidemiological studies have been carried out to address the association between chlorination and cancer mortality (see, e.g., 9,30,44). Comprehensive reviews have been written by Wilkins, et al. (54), Shy and Struba (42), and Crump and Guess (12). While differences of opinion with respect to existing evidence are still considerable, prudence dictates increased efforts to reduce the organic load in water destined for drinking. In February 1978, EPA amended the National Interim Primary Drinking Water Regulation by setting a maximum contaminant level (MCL) at 0.1 mg/l for trihalomethanes in community water systems serving populations greater than 75,000 persons and by specifying trihalomethane monitoring requirements for smaller communities. To meet these regulations, some cities have to remove or reduce the content of precursor-organics in raw water prior to its treatment with chlorine, which means that the burden of dealing with the high organic load falls on municipalities.

Waterborne Infectious Diseases

Agricultural wastes also are important potential sources of infection. Leachates from barnyards and feedlots carry animal-disease agents. Residues and litter from crops, orchards, and forestry operations are often sources of plant diseases and breeding places for insects.

Many animal diseases are infections shared by humans and other vertebrates. Table 20 shows selected diseases of worldwide distribution and/or relevance in the United States. The list is by no means all inclusive. It is, however, illustrative of a number of diseases shared by animals and humans for which water is known or suspected to be the route, or one of several routes, of transmission.

Agricultural Chemicals

According to a recent FDA report, more than 300 exotic chemical compounds are in use in the agricultural sector of the United States and other countries (39). The word "pesticide" encompasses categories of chemicals such as:

- insecticides—agents designated to control insect pest infestations of plants, animals, and humans;
- herbicides or defoliants—chemicals designated to control undesirable plants in the vicinity of beneficial plants (including aquatic plants);
- fungicides—chemicals used for control of fungal growth;
- rodenticides—chemicals that control rodents that would otherwise consume farm products;
- fumigants—gases or aerosols used to control pest organisms in the soil or in buildings; and
- larvicides and molluscicides—agents that control undesirable larval or mollusk populations in terrestrial or aquatic environments.

Historically, the use of pesticides has been of great value to society. For example, pesticides have helped control insect carriers of various communicable diseases (typhus, malaria) and have increased the agricultural output of food. Tschirley (48) has pointed out that despite intensified and accelerated research on alternative methods of pest control, there will probably be some continuous need for chemical pesticides. He has stated that "agricultural scientists cannot conceive of producing an adequate supply of food, feed, and fiber on the acreage now used for agriculture without judicious use of pesticides."

The unauthorized or careless use of pesticides may, and has been known to, cause harm. For some pesticides the margin of error is very small (48). Acute effects from unintended exposure to a large dose of toxic chemicals have been recognized. Quite another matter is the question of the impact of chronic human exposure to trace levels of pesticides distributed in the environment. This issue is much more complex, sensitive, and unsettled.

When pesticides are applied, it is very difficult to avoid an exposure of nontarget organisms in the vicinity. Some chemicals decompose readily and rapidly in the soil and thus are of little concern. Others, however, tend to persist for an appreciable length of time and become widely distributed in the environment, across land, water, and air.

Some resistant and fat-soluble pesticides tend to concentrate in animal tissues and to magnify biologically in the successive steps in the food chain. The concern over such persistence and accumulation in the environment and also in tissues of fish, birds, wild and domestic animals, and humans has brought notoriety to one group of insecticides, the chlorinated hydrocarbons. Other agricultural chemicals may be contaminated with a toxic byproduct of manufacture, dioxin. Many chemicals, currently banned, may continue to reside in the environment, being carried by and deposited in water which is then applied to other uses. The following discussion is illustrative of the concern in this complex and difficult area over past and

Table 20.—Selected Infections and Infestations Shared by Humans and Vertebrate Animals

Disease	Causative organism	Principal animals involved bacterial diseases	Known geographical distribution	Probable means of spread
Anthrax	Bacillus anthracis	Cattle, sheep, goats, horses, and wild herbivorous animals	Worldwide	Occupational exposure (hand dead animals) occasionally recreational exposure, from wounds or insect bites. Rarely airborne or foodborne. Waterborne in animal to animal transfer
Brucellosis	Brucella abortus Brucella melitensis Brucella suis Brucella canis	Cattle Goats and sheep Swine, caribous Dogs	Worldwide	Occupational exposure. Foodborne. Waterborne in animal to animal transfer
Melioidosis	Pseudomonas pseudomallei	Rodents, sheep, goats, horses, swine, nonhuman primates, and kangaroos	Asia, Australia, East India, South America, and United States	Exposure and ingestion. Organism lives in soil and water
Salmonellosis	Salmonella spp. (2,000 serotypes)	Poultry, swine, cattle, horses, dogs, cats, wild animals and birds, reptiles, amphibia, and crustacea	Worldwide	Ingestion, occupational and recreational exposure. Wound infection
Staphylococcus	Staphylococcus spp.	Domestic animals	Worldwide	Ingestion and contact
Streptococcus infections	Streptococcus species. Some species host-specific and only accidentally are the cause of disease in humans	Domestic animals	Worldwide	Ingestion and contact
Tuberculosis	Mycobacterium bovia	Cattle, nonhuman primates	Worldwide, except for countries that have eliminated the disease in cattle	Ingestion, inhalation, and occupational exposure Organism is capable of surviving in water
Tularemia		Rabbits, dogs, cats, rodents, and sheep	Circumpolar in northern hemisphere of America, Europe and Asia	Occupational (hunters) and recreational exposure to water, insect bites, and ingestion

SOURCE: Abstracted from Cech, 1983. Original source: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, Center for Infectious Diseases and the Office of Biosafety, Atlanta, Ga., and the University of Texas School of Public Health, Health Science Center, Houston, Tex. Revised in 1982. Courtesy of Professor James Steele, D.V.M.

present uses. A number of new products enter the agricultural market every year.

Chlorinated Hydrocarbons

Chlorinated hydrocarbons include Aldrin, Dieldrin, Endrin, Chlordane, Heptachlor, Oxychlordane, and Heptachlor Epoxide. (These compounds are grouped under the common term "cyclodienes.") Tables 21 and 22 illustrate pesticide concentrations reported in animal milk and human milk. Cyclodiene insecticides have been recognized as animal carcinogens. NAS (36) has characterized this group as "the most hazardous of all pesticides because of their persistence, fat storage, and central nervous system target site." In conclusions and recommendations on cyclodiene pesticides, the NAS report states:

> The cyclodiene insecticides—particularly the persistent expoxides, Dieldrin, Endrin, Heptachlor Epoxide, Oxychlordane—present the greatest hazards of all residual pesticides in water. At low dosages, they are highly active hepatocarcinogens and have a dangerous effect on the central nervous system of man and higher animals, leading to apparently irreversible changes in encephalographic and behavioral patterns . . . .

Table 21.—Organochlorine Insecticides in Illinois From Cow's Milk (ppm)

Insecticide	1971	1972	1973	Average
Chlordane	0.02	0.04	0.06	0.05
DDT	0.05	0.02	0.03	0.03
Dieldrin	0.08	0.04	0.08	0.07
Heptachlor . . .	0.03	0.03	0.05	0.05
Lindane	Trace	0.02	0.03	0.02

Note: Of 200 Samples analyzed, 87% were positive for chlordane, 92% for dieldrin, 93% for heptachlor, and 81% for lindane.

SOURCE: A. Curely and R. Kimbrough, "Chlorinated Hydrocarbon Insecticides in Plasma and Milk of Pregnant and Lactating Women, *Arch. Environ. Health*, vol. 18, 1969, pp. 156-164.

Table 22.—Pesticides in Human Milk

	Concentration, ppm	
Insecticide	Mean	Range
Dieldrin	0.0073	0.0029-0.0146
Heptachlor epoxide	0.0027	<0.0001-0.0044
DDT-T	0.0027	0.0404-0.1563

SOURCE: A. Curley and R. Kimbrough, "Chlorinated Hydrocarbon Insecticides in Plasma and Milk of Pregnant and Lactating Women," *Arch. Environ. Health*, vol. 18, 1969, pp. 156-164.

and further:

> In light of the above and taking into account the carcinogenic risk projections, it is suggested that very strict criteria be applied when limits for Dieldrin, Heptachlor, and Chlordane in drinking water are established.

According to NAS (36), perhaps 600 million pounds of these compounds have been dispersed into the soil, air, water, and food of the United States during the last several decades, and little is truly known about the fate of these compounds. It is recognized, however, that they are very stable compounds and, because of certain properties, become widely distributed throughout the environment.

Traces of these insecticides and their stable byproducts have been found in water nearly everywhere in the United States. The following average concentrations were reported by Breidenback and coworkers in 1967 (5):

Aldrin, <0.001—0.006 parts per billion (ppb)
Dieldrin, 0.08—0.122 ppb
Endrin, 0.008—0.2144 ppb
Heptachlor, 0—0.0031 ppb
Heptachlor Epoxide, 0.001—0.008 ppb.

Samples of finished drinking water taken in the late 1960's and early 1970's from the Mississippi and Missouri Rivers were positive for Dieldrin, Endrin, and Chlordane. Surveys of drinking water have identified traces of cyclodienes in public water supplies in Miami, Seattle, Cincinnati, New Orleans, and other cities. Water treatment apparently is incapable of totally removing these pesticides even with activated carbon filters (36).

Pesticides are regulated under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). This act, as Tschirley (48) pointed out, is essentially a "labeling law." It allows the registration of so-called "economic poisons" by the U.S. Department of Agriculture (USDA) in situations where products are designated for interstate commerce. It further allows the seizures of unregistered or insufficiently labeled pesticides. In 1972 an amendment to FIFRA was passed, giving EPA the authority for control over end-uses of pesticides.

The cyclodiene insecticides Aldrin and Dieldrin were banned by EPA on October 1, 1974. Chlorodane and heptachlor registrations were suspended for use on agricultural crops on April 1, 1976. DDT was another chlorinated hydrocarbon insecticide in widespread use from World War II until its ban in 1972.* Because of its slow biodegradation and high-fat solubility, this chemical also became widespread in the environment. DDT has been detected in milk and many other food products. Table 23 shows daily dietary intake estimated for an average 16- to 19-year-old U.S. male in the period 1965-70. The significance of these residues in the environment is not adequately known.

Dioxin

Contamination of irrigation water with herbicides was reported by the Federal Water Pollution Control Administration in 1968. In recent years the herbicide of phenoxy-type 2,4,5-T and also 2,4,5-TP (Silvex) have received much attention, mainly in connection with their associated chlorinated dioxin, TCDD (or 2,3,6,8-tetrachlorodibenzo-p-dioxin). By itself, 2,4,5-T (or 2,4,5-trichlorophenozyacetic acid) herbicide is only moderately toxic. However, it is now known that manufacturing of 2,4,5-T herbicide is accompanied by formation of an extremely toxic byproduct, TCDD, or dioxin, and that this dioxin may be present as a contaminant of technical grade herbicide 2,4,5-T and also Silvex.

Table 23.—Pesticides in Diet

	Daily dietary intake, mg						
Pesticide	1965	1966	1967	1968	1969	1970	6-yr average
DDT	0.031	0.041	0.026	0.019	0.016	0.015	0.025
DDE	0.018	0.028	0.017	0.015	0.011	0.010	0.017
DDD	0.013	0.018	0.013	0.011	0.005	0.004	0.011
DDT-T	0.062	0.087	0.056	0.045	0.032	0.029	0.053

SOURCE: National Academy of Sciences, National Research Council, *Drinking Water and Health* (Washington, D.C.: U.S. Government Printing Office, 1977).

The President's Scientific Advisory Committee (Panel on Herbicides) moved in 1971 that, in the future, production of 2,4,5-T herbicide shall not contain more than 0.1 mg/kg of dioxin as a contaminant (it has not been feasible to produce 2,4,5-T herbicide totally free of dioxin). Existing stock manufactured before 1971 was allowed to be marketed only if dioxin was limited to 0.5 mg/kg.

According to the Council on Scientific Affairs of the American Medical Association Advisory Panel on Toxic Substances (3), at one time as much as 70 ppm of the dioxin TCDD was present in the commercial formulation of these herbicides. Since manufacturers have become aware of the problem, products contain dioxin impurities at levels normally below 0.01 ppm. Dioxin may be generated during incineration of some chlorinated compounds in industrial and municipal wastes and by burning vegetation treated with phenoxy-type herbicides.

Dioxin is not particularly soluble in water, but it binds tightly to clay particles and thus can be carried into water by sediment transport. This compound is toxic at extremely low levels, much below the reliable limits of detection. Dioxin "may well be one of the most toxic substances known to man," according to the Advisory Panel on Toxic Substances of the American Medical Association (3). Symptoms of exposure to dioxin have been reported as chloracne, impaired liver function, nephropathy, irritation of gastrointestinal tract, depression, and irritation of nervous system (36). Pathological changes in the liver, peripheral nerves, blood-forming organics, and the reticuloendothelial system (3) have also been noted.

In assessing the situation with regard to toxicity and the long-term health effects of dioxin, the Advisory Panel on Toxic Substances formed by the Council on Scientific Affairs reported that "although data from studies on experimental animals tend to support some of these claims, it is not certain that the animal data are extrapolatable to man" (3). The council therefore recommended a continuation and expansion of the studies of exposed or allegedly exposed persons to alert all physicians through American Medical Association publications to the possible adverse effects and signs of dioxin exposure and to enlist their cooperation in the collection of vitally needed information.

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*DDT and DDT-related products, DDD (2,2-(p-chlorophenyl)-1, 1-dichloroethane) and DDE (2,2-bis-(p-chlorophenyl)-1, 1-dichloroethylene) are collectively known as DDT-T.

DBCP

Another example of recent concern over agricultural chemicals that may still be polluting the water supply and affecting humans is DBCP (dibromochloropropane)—an agricultural chemical widely in use prior to 1977. In 1977 it was reported that DBCP had caused infertility in male factory workers exposed to it. Studies initially conducted in the agricultural chemical plant in Lathrop, Calif., and later in three other DBCP manufacturing plants, found a total of 100 cases of abnormally low-sperm counts (49). In September 1977, DBCP was banned from manufacturing and agricultural application in the United States.

According to Glass and associates (20), workers who applied this chemical in the field situation were probably the largest group of people exposed to this nematocide. Glass pointed out that prior to the ban on DBCP in 1976, several thousand independent farmers and professional pesticide applicators in California alone applied more than 1 million pounds of this chemical to more than 50,000 acres of land.

Public Health Effects

In 1977, the NAS National Research Council reported that a large number of synthetic organic compounds had been detected in drinking water in the United States. From the compounds known to be present in water, a fraction were selected for detailed review of their health significance. Among compounds selected for scrutiny were 55 pesticides and 74 nonpesticide organic chemicals. It was indicated that some of the pesticides studied had not been observed in drinking water but were included because of their widespread and heavy use.

Of the pesticides studied, 23 compounds were identified for which positive data on carcinogenesis existed. These compounds are listed in table 24. The category of confirmed animal carcinogens included such well-known pesticides as Dieldrin, Heptachlor, Chlordane, DDT, Lindane, B-BHC, Aldrin, Kepone, and several others. The insecticides Endrin and Heptachlor Epoxide and the fumigant Bis (2-chlorethyl ether) were classified as "suspected animal carcinogens."

In this NAS study, data to estimate risk from human exposure veried widely. For some compounds it was possible to estimate acceptable daily intake (table 25); for others it was not possible (table 26). As a result of its assessment, NAS (36) concluded that:

> The potential for existing concentrations of organic pesticides and other organic contaminants in drinking water to adversely affect

Table 24.—Categories of Known or Suspected Organic Chemical Carcinogens Found in Drinking Water

Compound	Highest observed concentrations in finished water, µ/liter
Human carcinogen:	
Vinyl chloride	10
Suspected human carcinogens:	
Benzene	10
Benzo (a) pyrene	D
Animal carcinogens:	
Dieldrin	8
Kepone	ND
Heptachlor	D
Chlordane	0.1
DDT	D
Lindane (γ-BHC)	0.01
β-BHC	D
PCB (Aroclor 1260)	3
ETU	
Chloroform	366
α-BHC	D
PCNB	ND
Carbontetrachloride	5
Trichloroethylene	0.5
Diphenylhydrazine	1
Aldrin	D
Suspected animal carcinogens:	
Bis (2-chloroethyl) ether	0.42
Endrin	0.08
Heptachlor eposide	D

D = Detected but not quantified; ND = Not detected.

SOURCE: National Academy of Sciences, National Research Council, *Drinking Water and Health* (Washington, D.C.: U.S. Government Printing Office, 1977).

Table 25.—Organic Pesticides and Other Organic Contaminants in Drinking Water, Concentration, Toxicity, ADI, and Suggested No-Adverse-Effect Levels

Compound	Maximum observed concentrations in H_2O, μg/liter	Maximum dose producing no observed adverse effect, mg/kg/day	Uncertainty factor[a]	ADI[b] mg/kg/day	Suggested no-adverse-effect level from H_2O, μg/liter assumption[c]	
					1	2
2,4-D	0.04	12.5	1,000	0.0125	87.5	4.4
2,4,5-T		10.0	100	0.1	700	35.0
TCDD		10^{-5}	100	10^{-7}	7×10^{-4}	3.5×10^{-5}
2,4,5-TP	detected[d]	0.75	1,000	0.00075	5.25	0.26
MCPA		1.25	1,000	0.00125	8.75	0.44
Amiben		250	1,000	0.25	1,750.0	87.5
Dicamba		1.25	1,000	0.00125	8.75	0.44
Alachlor	2.9	100	1,000	0.1	700.0	35.0
Butachlor	0.06	10	1,000	0.01	70.0	3.5
Propachlor		100	1,000	0.1	700.0	35.0
Propanil		20	1,000	0.02	140.0	7.0
Aldicarb		0.1	100	0.001	7	0.35
Bromacil		12.5	1,000	0.0125	87.5	4.4
Paraquat		8.5	1,000	0.0085	59.5	2.98
Trifluralin (also for Nitralin and Benefin	detected	10	100	0.1	700.0	35.0
Methoxychlor		10	100	0.1	700.0	35.0
Toxaphene		1.25	1,000	0.00125	8.75	0.44
Azinphosmethyl		0.125	10	0.0125	87.5	4.4
Diazinon		0.02	10	0.002	14.0	0.7
Phorate (also for Disulfoton)		0.01	100	0.0001	0.7	0.035
Carbaryl		8.2	100	0.082	574	28.7
Ziram (and Ferbam)		12.5	1,000	0.0125	87.5	4.4
Captan		50	1,000	0.05	350	17.5
Folpet		160	1,000	0.16	1,120	56.0
HCB	6.0	1	1,000	0.001	7	0.35
PDB	1.0	13.4	1,000	0.0134	93.8	4.7
Parathion (and Methyl parathion)		0.043	10	0.0043	30	1.5
Malathion		0.2	10	0.02	140	7.0
Maneb (and Zineb)		5.0	1,000	0.005	35	1.75
Thiram		5.0	1,000	0.005	35	1.75
Atrazine	5.1	21.5	1,000	0.0215	150	7.5
Propazine	detected	46.4	1,000	0.0464	325	16.0
Simazine	detected	215.0	1,000	0.215	1,505	75.25
Di-n-butyl phthalate	5.0	110	1,000	0.11	770	38.5
Di (2-ethyl hexyl)	30.0	60	100	0.6	4,200	210.0
Hexachlorophene	0.01	1	1,000	0.001	7	0.35
Methyl methacrylate	1.0	100	1,000	0.1	800	35.0
Pentachlorophenol	1.4	3	1,000	0.003	21	1.05
Styrene	1.0	133	1,000	0.133	931	46.5

[a] Uncertainty factor—the factor of 10 was used where good chronic human exposure data was available and supported by chronic oral toxicity data in other species, the factor of 100 was used where good chronic oral toxicity data were available in some animal species, and the factor 1,000 was used with limited chronic toxicity data.

[b] Acceptable Daily Intake (ADI)—Maximum dose producing no observed adverse effect divided by the uncertainty factor.

[c] Assumptions: Average weight of human adult = 70 kg. Average daily intake of water for man = 2 liters.
1. 20% of total ADI assignment to water; 80% from other sources.
2. 1% of total ADI assigned to water; 99% from other sources.

[d] Detected but not quantified.

SOURCE: National Academy of Sciences, National Research Council, *Drinking Water and Health* (Washington, D.C.: U.S. Government Printing Office, 1977).

Table 26.—Organic Pesticides and Other Organic Contaminants Found in Drinking Water, With Insufficient Data on Chronic Toxicity to Calculate an Acceptable Daily Intake

Concentration	Highest concentration in finished water, μg/liter
Acetaldehyde	0.1
Acrolein[a]	
Bromobenzene	detected[b]
Bromoform	detected
Carbon disulfide	detected
Chloral	5.0
Chlorobenzene	5.6
Cyanogen chloride	0.1
1, 2-Dichloroethane	21.0
2, 4-Dichlorophenol	36.0
2, 4-Dimethylphenol	detected
e-Caprolactam	detected
Hexachloroethane	4.4
o-Methoxyphenol	detected
Methyl chloride	detected
Methylene chloride	7.0
Phenylacetic acid	4.0
Phthalic anhydride	detected
Propylbenzene	<5.0
t-Butyl alcohol	0.01
Tetrachloroethane	4.0
Tetrachloroethylene	<5.0
Toluene	11.0
Trichlorobenzene	detected
1, 1, 2-Trichloroethane	1.0
Nicotine	3.0
Methomyl[a]	
Cyanazine	detected
Xylene	<5.0

[a] Not detected in finished drinking water.
[b] Detected = detected but not quantified.

SOURCE: National Academy of Sciences, National Research Council, *Drinking Water and Health* (Washington, D.C.: U.S. Government Printing Office, 1977).

health cannot be answered with certainty at this time. The key issue is whether or not certain organic chemicals found in very low concentrations can cause or increase the rate of cancer development in man. Even though several of these chemicals have demonstrated carcinogenicity in laboratory animals, the extrapolation of such results to man remains difficult for a number of reasons.

Among the reasons for uncertainty was the difference in dosage: the doses at which tests are conducted are many times greater than the concentrations of the same chemicals found in drinking water. Therefore, risk at low levels of exposure is derived, out of necessity, by extrapolation from high doses. "There is no real hard evidence," it was said, "that low-level exposure to the same chemical produces cancer." The 1977 report summarized NAS's position on pesticide use as follows:

> Demonstration that a pollutant is carcinogenic, and application of nonthreshold risk estimates to it, do not imply that its use must be prohibited. Such a prescription might itself give rise to even greater risks to health or other disadvantages. In some cases, a net risk must be estimated, and society must attempt to use the pollutant in such a way as to minimize risk and maximize benefit.

DATA COLLECTION

Water-Quality Monitoring

The only coherent nationwide information on water quality is provided by a monitoring system established by USGS in 1975. The National Stream Quality Accounting Network (NASQAN) is an assemblage of monitoring stations located in different river basins and subbasins. The size of the network is increasing and now numbers over 500 stations, of which approximately half are in the Western United States. The same data have been collected on the same pollutants since the inception of the network.

The stations included in the NASQAN network were established to measure the amount of surface water flowing out of a watershed. For this reason, they are not necessarily located where water is used. In some cases, the watersheds which the stations were established to monitor are located upstream from major pollution sources. In other cases, the station may be located substantially downstream of such sources. For those pollutants that do not degrade or otherwise change in the water, downstream monitoring locations may be adequate. However, some water pollution problems are quite localized. For example, the depletion of oxygen in a stream near the point where municipal sewage or agricultural organic wastes enter may produce serious problems near the point of discharge and be undetectable by the time the river reaches a NASQAN station. Moreover, NASQAN stations do not measure all pollutants. Most toxic organic chemicals, such as those used as pesticides, are not measured. In many cases, monitoring equipment may not be able to measure low concentrations of pollutants which nonetheless may have a significant effect on water quality and long-term implications for human and animal health.

Additional information on water quality is collected by State water pollution authorities. The usefulness of this information, however, is limited because of variations in State programs and monitoring procedures and because the data often cannot be easily obtained. One useful source of State-generated information is the set of reports that State authorities are required to submit to EPA every 2 years under section 305(b) of the Clean Water Act.

No systematic, comprehensive monitoring of ground water quality exists. Federal legislation adopted subsequent to the Clean Water Act has addressed ground water contamination from selected sources, principally hazardous waste sites. But this legislation (the Resource Conservation and Recovery Act, or RCRA, and the Comprehensive Environmental Response, Compensation, and Liability Act, "Superfund" program) lacks clearly stated ground water-quality objectives.

The Safe Drinking Water Act contains a provision that allows the Federal Government to attempt to prevent pollution of specific aquifers designated as the sole source of drinking water supplies. Since its passage in 1975, nine aquifers have been designated as sole-source aquifers. Approximately 12 additional aquifers are in various stages of investigation for inclusion.

In 1979, EPA began to integrate its various legislative authorities for ground water quality into a coherent ground-water protection strategy. In a draft published in 1979, the Agency has proposed water-quality goals for ground water and alternative means of achieving those goals. The success with which these goals are met is clearly related to the effectiveness of a ground-water quality-monitoring program, which has yet to be established.

CONCLUSIONS

To evaluate the relationship between water quality and agriculture in the Western United States, it is necessary to consider: 1) the effects of agricultural uses on water quality for other uses, and 2) the effects of water quality on various agricultural uses. In some cases, these are linked in that an agricultural water use may create a quality problem that affects succeeding users, including agricultural users. In other cases, water-quality changes that are deleterious to agriculture may result from nonagricultural water uses or simply from the processes that determine natural water quality.

The types of possible water pollution are varied and can arise from different uses. They can be summarized in eight general categories:

1. municipal sewage and other oxygen-demanding wastes,
2. infectious agents,
3. synthetic organic chemicals,
4. inorganic chemicals and mineral substances,
5. sediments,
6. plant nutrients,
7. radioactive substances, and
8. heat.

The highest quality water required in agriculture is for domestic farm consumption. Almost all of the water used in this way is taken from water wells. The quality of this water is not routinely monitored, nor is it subject to any routine treatment prior to use, as is the case with municipal domestic water supplies. The quality of this water source is particularly susceptible to degradation because of the many potential sources of contaminants in the farm environment.

Water that is safe for human consumption can also be used by livestock, but some stock can tolerate water of a somewhat poorer quality. It is suspected that many animal diseases can be transmitted by contaminated water. Water for livestock use can either be polluted by natural sources, such as a high natural mineral content of the water or a deficiency of some necessary mineral, by algae "blooms" associated with the discharge of agricultural fertilizers into the water, or by the presence of diseased animals.

The quality of water used in irrigation is very important. Also important is the way in which this irrigation water is applied to the soil and the characteristics of the soil itself. As some water applied in irrigation is lost to evapotranspiration during the growth of plants, the salts contained in that water are left behind in the soil. If this situation is not eventually corrected by the application of additional water to leach the salts out of the soil and return them to the river, this salt buildup will ultimately restrict agricultural productivity. The return flows from this leaching process raise public health implications for downstream drinking-water users.

Present knowledge of water constituents and associated tolerance limits for various users is far from complete. Some tolerance levels are available, however, for evaluating the suitability of water for particular uses. Increased research efforts would contribute to improved information on water-quality aspects of agricultural water use.

The possibility of supplementing irrigation water supplies in some areas with municipal and industrial wastewater is receiving increased attention. The suitability of such water for agriculture depends on its level of contamination and the type of treatment it receives. The most serious reservations concerning this practice have to do with viruses and heavy metals, which are particularly difficult to remove by existing water treatment. There is concern that viruses may remain viable in the water or the soil for long periods of time and pose a significant health threat to both humans and animals.

Water contamination resulting from agricultural practices involves many natural and chemical nonpoint sources of pollution that are particularly difficult to detect and treat. The exact effect of any single practice will be largely determined by the nature of the substance introduced into the water, the concentration at which it is introduced, and the natural capacity of the soil-water system to deal with that substance. Effects may range from increased sedimentation to complicated chemical reactions from synthetic agricultural pesticides that are suspected of causing serious human health problems ranging from cancer to nervous disorders. In all cases, more efficient management of potential sources of water pollution from agriculture will do much to decrease the severity of the impacts.

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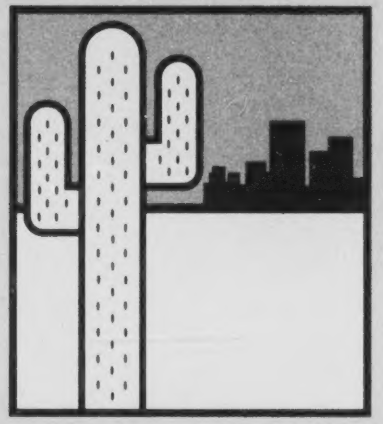

V

Institutions Affecting Western Agricultural Water Use

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Chapter V

Institutions Affecting Western Agricultural Water Use

Distribution and use of Western water resources for sustainable agriculture are subscribed by two institutional forces: first, water laws that establish rights and duties with respect to the use of water and, second, in recent years, economic institutions that allow water to be transferred between users and uses. These institutions and their associated rules influence the adoption of water-related technologies and effective water management for sustainable Western agriculture. The Western agricultural water user is, at best, moderately uncertain about water use because it is unclear how these rules might change as demands increase.

This chapter first describes the major elements of Western water law as they affect water use in agriculture. In light of growing demands on existing supplies and few opportunities to acquire new inexpensive water, water economics is receiving increased interest as a vehicle for reallocating water among competing demands. The chapter next highlights some of the factors contributing to increased demand for Western water and then examines factors affecting the feasibility of water markets and the impact of economics on the adoption of water-related technologies for sustainable Western agriculture.

WESTERN WATER DEVELOPMENT

History

In the early days of the United States, when Western lands were owned in a proprietary capacity by the United States, a precondition to settlement and development of the water-short West was a secure water supply. Farmers and some miners diverted water through networks of small river dams and canals for use on distant lands. Other settlers and miners located along streambanks claimed rights to water in those streams. In early conflicts, the courts generally followed local rules and custom and ruled against riverbank (riparian) settlers on the grounds that they did not legally meet the riparian doctrine's fundamental requirement, ownership of the land.

Perhaps more important, water was already being used consumptively far away from the stream to meet the needs of farming, mining, and other purposes in this arid/semiarid region. In contrast to the humid and water-abundant Eastern United States, it became increasingly important in the West to ensure that upstream diversions would not deplete supplies on which downstream investments depended. Thus began an early judicial recognition of the right of the first user (or appropriator) of surface water in Western lands to have the superior right to that water. "First in time, first in right" became the local rule.

Gradually, Federal programs became directly involved in shaping the character of Western agriculture and water use. Two Federal laws had particular impact on early Western agricultural and water development. First, the Desert Land Act of 1877 severed water rights from the public land and granted each State the right to adopt its own system of water law to govern the appropriation of nonnavigable waters. In the act, Congress also recognized that farmers in the arid/semiarid Western lands could not operate successfully on the 160-acre parcels of land provided by the Homestead Act of 1862 and so granted full title to 640 acres

Box E.—John Wesley Powell's "Blueprint for a Dryland Democracy"

John Wesley Powell, chronicler of American Indian languages, explorer of the Colorado River, and one of the most prominent Government scientists of his age, knew the West intimately. He watched with dismay as Western settlement followed Eastern models. In 1878, he presented a revolutionary plan to the United States Congress. It proposed to tailor agricultural development to the unique features of these dry lands.

As Wallace Stegner, a major American historian described it, Powell's plan had several important provisions regarding the size and shape of homesteads and their ownership. Stegner wrote:

> Water was the true wealth in a dry land; without it land is worthless or nearly so. And if you control the water, you control the land that depends on it. In that fact alone was the ominous threat of land and water monopolies. To prevent this—or to stop it for it was already beginning to happen, Powell made two proposals. One was that each pasturage farm should have within its 2560 acres twenty acres of irrigable land with a water right that was inseparable from the land . . . . Instead of rectangular parcels, therefore, Powell proposed surveys based on the topography, letting farms be as irregular as they had to be to give everyone a water frontage and a patch of irrigable soil.

The second part of Powell's proposal suggested that national surveys, conducted by a central Government scientific agency or settlers themselves, would choose irrigation or "pasturage" for their regions. Stegner wrote that "In either case, a homesteader would have a guaranteed water supply."

Powell's proposals were debated in Congress in 1878 and 1879. They were defeated by powerful Western delegations, Powell's scientific enemies, and the special interests of the day. Powell went on to suggest other far-reaching plans for the development of the arid West. But the Nation never fully used the insights of this man who understood "the unity of drouth."

SOURCE: Wallace Stegner, *Beyond the Hundredth Meridian: John Wesley Powell & the Second Opening of the West* (Lincoln, Nebr.: Universtity of Nebraska Press, 1982).

of land after 5 years of residency if a portion of the land were developed for irrigation within a specified period. Second, the Carey Act of 1894 granted 1 million acres of public land to each State containing arid lands on condition that the State provide for the necessary reclamation.

Under these laws Congress deferred to Western State appropriation doctrines for local nonnavigable water use. Since then, Federal water-related agencies have generally been required to comply with State laws in the appropriation of such water.*

Water Projects

The progress of water development in the Western United States has had a fundamental impact on the development of Western agriculture and on the kinds of water-related technologies developed and adopted. As more individuals became involved, mutual water companies or water cooperatives were formed to reduce conflict and ensure a fair distribution of water. Mutual irrigation companies frequently became formal corporate entities under State charters, with stock being issued to their members as evidence of proportionate voting rights in the election of company directors. Many other groups elected officers on the same voting basis as in formal corporations but operated as associations rather than as formally registered corporations. In some areas large-scale irrigation projects were organized and supported by foreign capital, primarily from the British (24). Today, many of the Western mutual irrigation companies are still significant water institutions, some having been transformed into major water management and power-generating organizations.

As the need for water increased, the trend in water-management development was for an increasing government role. Early State legislation authorized the creation of water supply and irrigation districts and provided formal organization and power to the districts to raise revenue for constructing water-conservation facilities such as dams, reservoirs, canals, and diversion structures. A further shift occurred with the passage of the Federal Reclamation Act of 1902 (Public Law 57-161). The features of large-scale construction projects called for a strong role by the Federal Government in particular, for substantial financial resources, technical expertise, and a geographic perspective convenient for interstate river basins.

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*See, for example, the Federal Reclamation Act of 1902, which requires the Secretary of the Interior to secure project waters in accordance with local law.

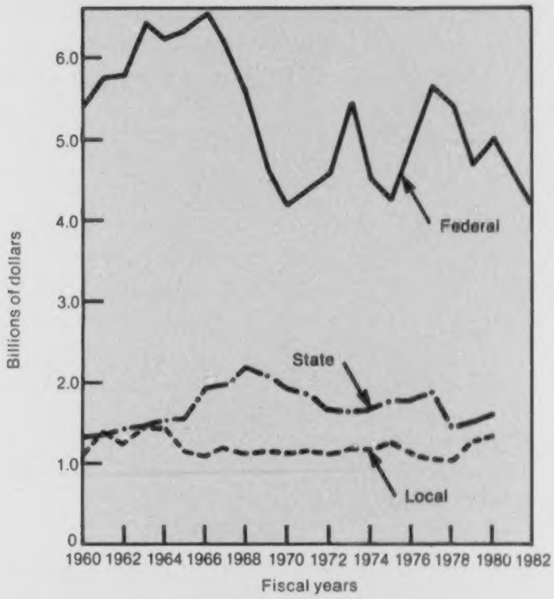
The 1902 Act provided for Federal subsidies to irrigators through a number of activities. First, it set up a revolving fund for irrigation development from moneys raised through the sale of public lands. Funds were to be used in constructing storage and power dams and for canal systems required for irrigation. Second, settlers were to receive their lands free in much the same way as under the Homestead Act (a 5-year residency requirement) but were to repay the costs of structures built by the Government within 10 years. Gradually, Federal subsidies were further extended to irrigation farmers in the form of interest-free loans for capital facilities, longer repayment periods, low interest rates, contributions to irrigation construction costs by other beneficiaries (especially power users), and a repayment formula that attempted to consider the irrigator's ability to pay.

The politics of these and other federally subsidized projects has been called "distributive," reflecting a political process whereby each element in an omnibus package is carefully designed to provide local benefits to a variety of community, user, and political interests (17). Congressional vote-trading determined who would get the initial Federal projects. This distributive process involved both upstream and downstream States in the arid/semiarid West. Growth in some areas was made possible in part through the consent of upstream users who, under less growth pressure at the time, believed they would eventually receive Federal assistance for water development (15). The apparent cost-free benefits to local communities provided incentives for sponsorship by the principal local political interests, and actual costs were distributed among general taxpayers. Clear standards for judging the long-term desirability of these projects based on costs and benefits to the Nation, were largely absent in these early decisions (18).

"Principles, Standards, and Procedures" (replaced in 1983 by the new "Economic and Environmental Principles and Guidelines") were developed pursuant to the 1965 Water Resources Planning Act to guide the planning and design of projects. The application of these criteria has led to conclusions that many projects are uneconomic and unjustified. Federal financing arrangements for water projects have been under attack particularly regarding the planning, design, and actual construction of projects whose costs are not adequately recovered (31). The fiscal criticism focuses on the overall costs to Government, including the costs of Government borrowing, and whether this should remain a priority in light of other Government concerns.

Reforms of existing Federal water-project repayment laws and practices that include more equitable cost-sharing arrangements and greater cost recovery from water users are underway and are likely to continue over the next several years (32). From its peak in 1965, Federal spending for water projects has generally declined (see fig. 26). Moreover, expenditures for water resources appear to be shifting away from massive new construction projects and toward rehabilitation and more efficient management of existing public works (27).

Figure 26.—Federal, State, and Local Spending for Water Resources, 1960-82[a]



[a]Actual State and local data for 1980-82 not available.

SOURCE: Congressional Budget Office from data supplied by the Congressional Research Service and the U.S. Department of Commerce, Bureau of the Census, U.S. Congressional Budget Office, *Public Works Infrastructure: Policy Considerations for the 1980's* (Washington, D.C.: U.S. Government Printing Office, 1983).

WESTERN WATER LAW

Water's special nature as both a natural resource and an essential social good has always made it subject to some public regulation to protect public interests. Until laws were developed, settlement of disputes over water rights was left to private means, often vicious and brutal. Early on, a clear interest developed to channel private grievances to public institutions, thereby bringing some order and equity to the process of water use and distribution.

The major State and Federal law doctrines that have developed to regulate water are fundamental in guiding decisionmaking on water distribution and use in the arid/semiarid West. They define the extent of a water user's rights as well as the extent of duties or constraints on those rights. The doctrines are key factors influencing decisions about the adoption of water-related technologies for sustainable agriculture.

The concept of priority in accordance with the date that use began gave birth to the term "prior appropriation" to describe the most common water-use system in the Western States. The fundamental principles established under this arrangement have been followed since its recognition by early courts. They are:

1. that water in its natural course is the property of the public and is not subject to private ownership;
2. that a vested right to use the water may be acquired by appropriation and application to beneficial use;
3. that the person first in time is first in right; and

4. that beneficial use is the basis, measure, and limit of the right (6).

This doctrine creates the right of private use of a public resource under certain conditions where the use has been declared to be a public one. Generally, a use is public when it is applied to a beneficial purpose, defined initially in State constitutions and statutes to be domestic, municipal, stock watering, irrigation, and certain industrial and power uses. More recently, it has also been defined in a few States (e.g., Colorado and Montana) to include instream flow (see app. C). Some State laws give a preference to one sector of use over another. Historically, in most Western States, strong rural representation has ensured agriculture a high position as a beneficial user.

An acquired water right in the Western States has two legal characteristics. First, the right is a real property right to use the resource, a right which if defined can be sold, bequeathed, or otherwise transferred so long as approved by the State water authority, a necessary condition to protect other appropriators. Second, it is a right to be exercised only when the water authorized for diversion under the right is available and applied to a "beneficial use." The water applied must also be "reasonable" for that use. If the rightholder cannot put it to reasonably beneficial use, the water remains a public resource to be passed to other appropriators. However, if the rightholder can beneficially use the water, it remains an individual's personal property while diverted within his/her delivery system and until it is returned back to the natural system (stream or aquifer).

State Level

States are involved with water regulation through their implied constitutional powers to create property rights and to protect and regulate their citizens through their police powers. State water law regulates use, not ownership, of water by granting and administering rights for use contingent on conformity with certain conceptions of "public interest" as developed by the political process.

The development of State water-law principles was influenced by early court decisions, some reinforcing and others frustrating local custom. Because of its reliance on precedent, the judicial arena has been slow to reflect contemporary scientific understanding of water as it operates in a dynamic, interconnected, surface-subsurface system. Western State legislatures and related local water institutions have had to become increasingly active in attempts to meet changing needs and resolve conflicts over use. While early legal doctrines remain the backbone of current State water law, innovative experiments also are underway in some States to adapt these principles to be more responsive to the increasing demands on limited supplies (discussed in app. C).

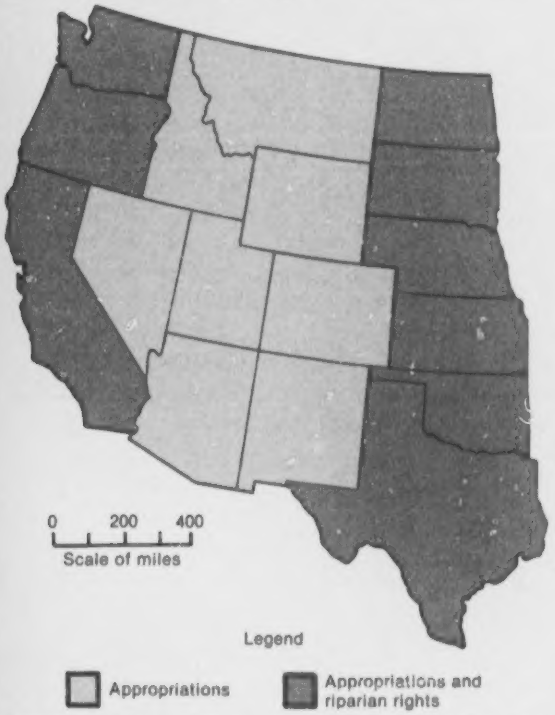
Surface and Ground Water Law

Major bodies of water law at the State level have developed for surface-water instream sources and ground water. Historically, each has been treated separately under the law and generally without regard to natural interconnections existing within the hydrologic cycle. The point at which water was diverted from its natural state and brought under control determined the legal classification (26).

The historical development of water law permitted each Western State to formulate solutions that fit local needs. Although each accepted the major concepts of prior appropriation, various State laws developed significant differences in their substantive and administrative aspects. Some with more humid areas integrated certain riparian rights with prior appropriation doctrine and developed *"mixed" systems.* Some "pure" appropriation States that had rejected the entire regime of riparian rights still applied some riparian concepts. The riparian doctrine of the water-abundant East was gradually entirely replaced by the *appropriation* doctrine in other States. Figure 27 identifies the general system of surface water law under which each of the 17 Western States operates.

Several States have adopted additional rules to protect water needs of users within a water-

Figure 27.—Surface-Water Law Systems in the Western States



SOURCE: G. E. Radosevich, *Western Water Laws and Irrigation Return Flow*, EPA-600/2-78-180 (Ada, Okla.: U.S. Environmental Protection Agency, 1978).

shed or river basin from future shortages caused by out-of-basin diversions and uses. These "basin of origin" statutes (see table 27) have taken a variety of approaches, from those that authorize inhabitants within the basin to reclaim water for future needs, to others that restrict transfers outside the basin to water that is determined to be surplus.

Ground water rights and legal systems developed more recently in the Western States, owing in part to reliance on surface supplies for the early settlements and in part to a lack of knowledge about subsurface supplies and the technologies to develop them. As knowledge of ground water increased and as subsurface supplies were in greater demand, and public regulation of withdrawal and use became more important. For legal purposes, ground water has commonly been divided into two classes: 1) underground streams which flow in known and definite underground channels, and 2) percolating waters which flow beneath the surface of the earth in no known or identifiable natural channels. These legal classes are often at variance with scientific evidence, since in many areas no natural distinctions actually exist. All ground water is presumed in law to be percolating water, rather than an underground stream which would be considered in law essentially the same as surface water.

For ground water, each Western State adopted and modified basic surface doctrines to fit its perceived needs. Four major legal doctrines developed. A few States took the English view of absolute ownership of ground water somewhat parallel to the *riparian* view of surface water—i.e., the owner of the land owned all of the water within or under it because this water was deemed to be part of the soil. The consequence was that a landowner had no liability for any use made of ground water even though that use might damage others (8). As it became more evident that ground water moved in subterranean aquifers and use of, or interference with, such water could affect other landowners, this common law rule was later modified in some States to limit the landowner to *reasonable use.*

Other doctrines developed with the growth in knowledge about the interconnection of ground and surface waters. Some Western States adopted the doctrine of *correlative rights* whereby each landowner was held to have rights in a common aquifer in proportion to the land overlying the aquifer. Many States applied the *appropriation doctrine* to ground water, requiring that rights could only be acquired by withdrawing the water and applying it to a beneficial use. Figure 28 identifies the basic ground water doctrines used by the 17 Western States; most States have modified these basic theories to some extent by legislation (e.g., the Arizona Ground Water Management Act, 1980 [Ariz. Rev. Stat. (45-512)]).

Recently, challenges to the validity of two State ground water statutes have raised con-

Table 27.—A Summary of Western Water Law

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Legal feature State	Water Law Doctrines Surface water	Ground water	Ownership	Evidence of water right	Basis of llocation	Criteria of allocation	Preference of use (order)	Date of priority	Appurtenance	Water rights registry	Water quality in rights	Forfeiture of rights[a]	Drainage rules	Basin of origin
1-ARIZ	P.A.	R.U.[b]	Public	Permit	B.U.	B.U.	1-2-3-4-5	D.O.A.	Strict	Original	Case	5 yrs	C.E. & C.L.[c]	Yes
2-CAL	P.A.&R.	C.R.	People	Permit[d]	B.&R.U.	B.&R.U.	1-2–	D.O.A. post 1914	Unlimited	Current	Case + Statute	5 yrs <1914 3 yrs >1914	Yes	
3-COLO	P.A.	P.A.	Public	S.W.-decree G.W.-permit	B.U.	B.U.	1-2 over 5	S.W.-1st step G.W.-D.O.A.	None	Original (computerized)	Case	–[e]	C.L. (modified)	Yes
4-IDA	P.A.	P.A.	State	License	B.U.	1 cfs/50 acres	1-2[f]	D.O.A.	Unlimited	Current (Limited)	Case	5 yrs	C.L.	
5-KAN	P.A. & R.[g]	P.A.	People	Permit	B.U.	1 to 2 acre-ft/ acre	1-2-5-6-3	D.O.A.			Case + Statute	3 yrs	C. L.	
6-MONT	P.A.	P.A	State	Permit	B.U.	1 miners feet per acre	None	D.O.A.		Original (Limited)	Case	–[e]	C.E.	
7-NEB	P.A. & R.[g]	R.U.[b]	Public	Permit	B.U.	1 cfs/70 acres or 3 acre ft/ acre	1-2 over 5	D.O.A.			Case	3 yrs	C.E.	Yes
8-NEV	P.A.	P.A.	Public	Permit	B.U.	Conditions & needs	None	D.O.A.		Original	Case	5 yrs	C.L.	
9-N.M.	P.A.	P.A.	Public	Permit	B.U.	B.U. & good agr. practices	None	D.O.A.		Original	Case	7 yrs + 1 yr after notice	C.L.	
10-N.D.	P.A.	P.A.	Public	Permit	B.U.	1 cfs/80 acres	1-2 & 5-6	D.B.U.			Case	3 yrs	R.D.	
11-OKLA	P.A. & R.[g]	P.A.	–	Permit[d]	B.U.	B.U.	None	D.O.A.	Strict	Current	Case	7 yrs	R.D.	Yes
12-ORE	P.A. & R.[g]	P.A.	Public	Permit	B.U.	B.U.	1-2-4–	D.O.A.	Strict	Original	Case	5 yrs	C.L.	
13-S.D.	P.A. & R.[g]	P.A.	People	License	B.U.	1 cfs/70 acre or 3 acre-ft/ acre	1–	D.O.A.		Original	Case	3 yrs	C.L.	
14-TEX	P.A. & R.[g]	A.O.	State	Permit[d]	B.U.	B.U.	1-5-2-4-3-7-6	D.B.U.		Current	Case	10 yrs	C.L.	Yes
15-UTAH	P.A.	P.A.	Public	Permit	B.U.	Nature of use	1-2	D.O.A.		Current	Case	5 yrs	C.E.	
16-WASH	P.A. & R.[g]	P.A.	Public	Permit	B.U.	Reasonably necessary & B.U.	None	D.B.U. & D.O.A. for permits		Current (computerized)	Case	5 yrs	C.E.	
17-WYO.	P.A.	P.A.	State	Permit	B.U.	1 cfs/70 acres	1-5	D.O.A.	Strict	Original	Case	5 yrs	Undecided	

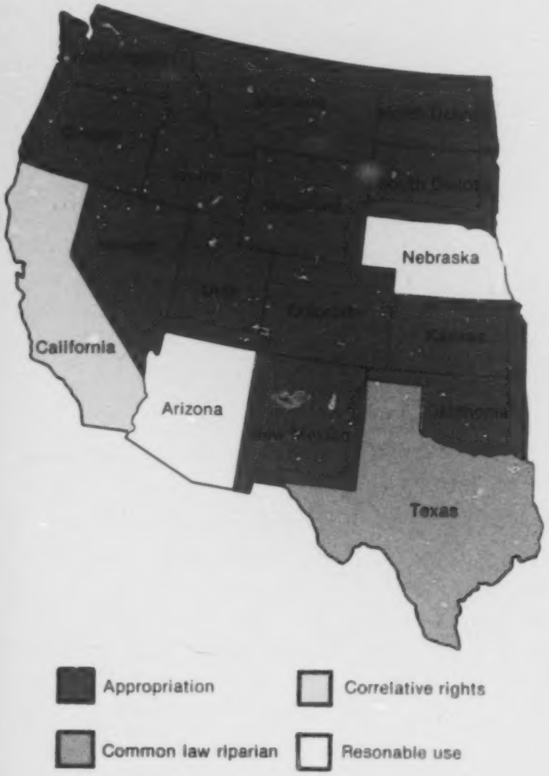
KEY:
A.O.—absolute ownership; B.U.—beneficial use; B.&R.U.—beneficial and reasonable use; C.E.—common enemy; C.L.—civil law; C.R.—corrective rights; D.O.A.—date of application; D.B.U.—date of beneficial use; G.W.—ground water; P.A.—prior appropriation; R.—riparian; R.D.—reasonable discharge. R.U.—reasonable use; S.W.—surface water

Column 7: 1—domestic and municipal; 2—agricultural (irrigation); 3—power; 4—mining; 5—manufacturing and industrial; 6—recreation; 7—navigation.
Column 9: Original—initial filing recorded; Current—user must notify agency of name, use, place, etc., transfers unlimited.

[a] All States recognize loss by abandonment.
[b] Lack comprehensive ground water laws.
[c] C.E. = flood waters, C.L. = natural flows.
[d] Different types; not for 1914 rights, riparian rights, and percolation ground water.
[e] Ten years is evidence of abandonment.
[f] In mining districts, 4 over 2 and 5.
[g] All new water by prior appropriation.

SOURCE: Adapted from: G. E. Radosevich, *Western Water Laws and Irrigation Return Flow*, EPA-600/2-78-180 (Ada, Okla.: U.S. Environmental Protection Agency, 1978).

Figure 28.—Ground-Water Law Systems in the Western States



[a]Oklahoma has many characteristics that also place it in the correlative rights category.

SOURCE: Adapted from: G. E. Radosevich, *Western Water Laws and Irrigation Return Flow*, EPA-600/2-78-180 (Ada, Okla.: U.S. Environmental Protection Agency, 1978).

cern about some of the traditional precepts of Western water law. In particular, the U.S. Supreme Court in *Sporhase, et al.*, v. *Nebraska* (25), and the U.S. District Court in *El Paso* v. *Reynolds* (10), decisions addressed the legal grounds of two States, Nebraska and New Mexico, to protect their scarce water supplies. While noting a State's public interest and equity concerns over water, these courts declared water an "article of commerce" and held unconstitutional State antiexport statutes that placed an undue burden on interstate commerce. Because their scope or potential impact is unclear, these cases have increased the confusion about a Western State's proper role in protecting and conserving vital water resources for its own citizens in times of severe shortage. Conceivably, the impacts are regionwide (29). Several other Western States have laws similar to that declared unconstitutional in the *Sporhase, et al.*, v. *Nebraska* case.

Water Quality Under Traditional Doctrines

Water-quality considerations are noticeably absent in a majority of the surface and ground water doctrines of the Western States. The one exception is California, which has a statute making water quality a specific element of a water right. A California user can make the same demands on an agency to protect an interest in water quality as that in water quantity entitled under the water right (24).

An implied right of water quality exists under the doctrine of prior appropriation. In theory, water-right holders should be entitled to the quality of water existing at the time of its appropriation. In practice, however, if an individual believes a water right is being impaired because of upstream pollution, the only recourse in most cases will likely be a lawsuit based on common law doctrines of nuisance and trespass. Only a few courts have protected irrigation users from upstream polluters, and these cases have usually involved extreme instances of water degradation. Most of the cases relating to such pollution occurred in the early 1900's (24).

The extent to which an individual State water-right holder might be able to revive either appropriation or common law doctrines for water-quality purposes is questionable. Unless strict controls exist, water-quality deterioration will probably increase as development and water use intensify in the West. Some States more than others may experience severe water-quality problems and thus threaten an individual user's right.

Administration of Western Water Rights

In most of the West, rights to use water are regulated and administered on a comprehensive basis. Table 27 summarizes the administrative approaches developed by each of the 17 Western States to oversee the system of water rights. Commonly, a State officer, often designated the "State Engineer," holds one of the most powerful positions in State-level water institutions. This officer keeps records of water use, receives and approves applications for new water uses, appoints river commissioners or water masters to supervise the distribution of water in accordance with water rights of record, and institutes court actions to determine and adjudicate both surface and ground water rights.

The prominent approach used for providing evidence of a Western water right is the permit system (table 27, column 4). In some States, the final water right may be called a license or certificate. A few States have different classes of permits to enhance their ability to allocate and regulate the use of water among competing interests.

In the West, most States have well-established procedures governing the transfer of water rights (7). A water user or a purchaser of a water right generally is entitled to change the point of diversion, place, and nature of use of the right. However, as a procedural matter, before such a change may be made, the owner of the right must file a change application with the State water-rights administrator. The purpose of the change application is to give notice to other water users on the system of the changes proposed and to allow the administrator to determine whether or not the change can be approved without impairing other existing rights on the same watercourse. The general rule in most States is that an appropriator is entitled to rely on stream conditions substantially as they were when that individual made an appropriation, and any change that is proposed cannot adversely affect other existing water rights (7). The question of impairment usually arises in connection with return flow. This is particularly true with respect to irrigation uses where it is common for some of the irrigation water to return to the watercourse as return flow or seepage. If this is the case, and the return flow makes up a portion of the downstream water rights, the upstream irrigator is not allowed to diminish that return flow by changing his/her water right. However, subject to the caveat that a proposed change cannot impair other water rights, most States have adopted a fairly liberal policy with respect to proposed changes.

An unrestricted policy with respect to water transfers has caused a few States to reevaluate their historic practices in this area. For example, the Wyoming Legislature has provided that when considering a change application the State Engineer may consider: 1) the economic loss to the community and State as a result of the discontinued use, 2) the extent that such economic loss would be offset by the new use, and 3) whether there may be another source of water available to satisfy the new use. These criteria supplement the traditional consideration of whether or not there would be impairment of other rights. This legislation thus allows for at least some modest evaluation of the public interest in determining whether the proposed change should be approved. Montana has taken a more restrictive step in an effort to protect large agricultural rights in that State. The Montana Water Code prohibits a transfer of an irrigation right to an industrial use if the quantity of water involved exceeds 15 cubic feet per second. This provision appears to have been designed to preserve the agricultural industry in that State (7).

Administration of Western water rights has become particularly complicated regarding allocation of those rights. In practice, water is allocated not only on the basis of traditional water law doctrines that have developed for naturally flowing and underground water but also on the basis of contractual arrangements between water districts and water supply agencies. A Federal or State agency may have constructed a dam for water storage, with entitlement to this water being defined by agreement with a water district. Thus, the specific amount delivered to an individual farmer may be unique to the given water supply system and not be defined entirely by strict application of a priority-of-use system. For example, an individual farmer may receive water defined by combined flow and storage rights and also have access to water in an underground aquifer. Many irrigation farmers in the West have all three types of water. Identifying what a particular user can get, when, and how becomes complicated. In addition, in some States permits are issued for single purposes, so consolidated records may not be available to identify the amounts allocated to and uses approved for a particular individual.

Owing to lack of information, ineffective monitoring, and disagreement on the meaning of the standard, the doctrine of reasonable beneficial use has not proven to be a significant constraint on water use. The definition of reasonable use depends on the availability of water, methods of diversion, and purpose of use, and is subject to uncertainty until the specific facts and circumstances are examined.

More fundamental to influencing adoption of "water-saving" technology for Western agriculture is the requirement of use as the basis of a water right under the doctrine of prior appropriation. This concept may discourage water conservation because it emphasizes either using the full allocation of water or losing the right to the unused portion. It is frequently argued that those who operate more efficiently and thus save water or who salvage water that would otherwise go to "waste" have no assurance that they will be the beneficiaries of such socially responsible conduct (18).

Federal Level

Constitutional authority exists for Federal water control and regulation through the commerce, property, and general welfare clauses

Box F.—"Today's Decisions On Water Will Shape Future"

The following was excerpted from an article by W. W. Lessley, chief water judge for Montana, who retired at the end of 1982 after 33 years on the bench:

> Three great rivers flow through the state—The Yellowstone, the Clark Fork and the Missouri. Because of this fact, we are truly the Treasure State and seldom face loss of water; but now new forces move toward our water. The great need of sister states and those states farther to the south of us for our water is a threat to our complacency concerning this resource. The possibility of Federal concern and even intervention gives us pause.
>
> If we were asked today by any court or administrative body to show the amount of water we have and the beneficial use we make of it and our great need for it, we could not do those simple things.
>
> The reasons for this are many. Approximately 76 percent of our water and water rights are what we call "use rights." There are no records anywhere except the use of these rights over a great number of years. Many of them rest in the far territorial and early history of our state, and the memories of those on which we rely are now gone. The rest of the percentage is divided between appropriated rights and decreed rights. The appropriated rights, in many instances, are faulty in record or cannot be found in our courthouse records. The decreed rights are uncertain because some water users were never informed when judicial action was in process and the inadequacy of the handling of the findings.
>
> Now we face the future with water, but for how long? We have strength. We are at the headwaters. Every rancher knows [w]hat that means even on a simple irrigation ditch, let alone on the great Missouri.
>
> But we have weaknesses. We have great expanse of territory but few people and few representatives in the Halls of Congress. The lower basin states have many people and that means many senators and representatives and clout in the Congress!
>
> The future lies ahead. Those who can only see the water we now have and are smug about our water really don't think of these things.

SOURCE: *Bozeman Daily Chronical Centennial Edition*, Mar. 30, 1983.

of the Constitution. The Federal Government is involved directly in water issues in the Western United States through the Federal doctrine of reserved water rights, water quality and environmental protection legislation, and interstate and international compacts.

The Doctrine of Reserved Water Rights

Under the doctrine of reserved water rights, the Federal Government acts as public trustee to ensure adequate water supplies to fulfill the purposes of national parks, forests, Indian reservations, and other Federal lands. Water rights become "reserved" by implication whenever Federal land is withdrawn from the public domain and reserved for some specific use or purpose: It is now generally settled that when a Federal reservation occurs, enough unappropriated water is reserved to accomplish in a reasonable manner the present and future purposes for which Congress made the reservation [*Winters* v. *United States*, 207 U.S. 565 (1908), commonly known as the "Winters" doctrine]. The water so reserved must come from the watercourses arising on or flowing across the Federal lands set aside for the reservation. Federal reserved water rights are vested as of the date of the reservation, whether or not the water is actually put to use. These rights are superior to the rights of those acquired after the reservation date.

Perhaps the most significant of the reserved water rights, for purposes of Western agriculture, are those held by Western Indian tribes. Approximately 400,000 American Indians live on over 200 reservations in the West (table 28). Their situation is hardly distinguishable from that of other rural poor, except for one important difference: the unique status of the Federal reservation.

In recent years, attention has been drawn to quantification of these rights as non-Indian development has expanded in the West and pressures have increased on existing supplies. Opinions differ about whether quantification is desirable for Indian rightholders. On the one hand, these rights include those for future needs and opportunities; it may be unreasonable to require that such needs be quantified,

Table 28.—Indian Reservations and Rural Populations by Region and State

Regions	Number of reservations	Total population	Number of acres	Rural population	
				Percent of total population	Mean income (household)
California	76	6,824	502,712.68	22.7	$7,123
Intermountain:					
Idaho	4	4,849	683,505.23	NA	NA
Montana	7	24,137	5,870,984.49	80.2	$5,872
Oregon	4	2,718	821,945.32	43.3	$7,191
Washington	22	18,238	2,779,045.40	48.2	$7,200
Southwest:					
Arizona	17	173,412	24,710,019.26	82.4	$4,335
Colorado	2	2,144	902,897.00	NA	NA
Nevada	23	4,866	1,171,699.55	NA	NA
New Mexico	24	30,125	3,463,637.50	81.7	$4,617
Utah	4	1,961	1,133,730.31	65.1	$4,189
Northern Plains:					
North Dakota	4	16,735	2,143,046.07	86.5	$5,332
South Dakota	8	29,119	5,962,418.35	70.5	$4,556
Wyoming	1	4,435	1,886,556.00	NA	NA
Southern Plains:					
Kansas	4	3,009	26,476.00	NA	NA
Nebraska	3	2,601	72,672.85	NA	NA
Oklahoma	27	81,264	1,644,913.12	48.9	$5,389
Texas	2	1,000	4,473.00	15.2	$7,373

NA = data not available.

SOURCE: Finan, et al., 1982. Original source: U.S. Department of Commerce, *Federal and State Indian Reservations* (Washington, D.C.: U.S. Government Printing Office, 1974); and *1970 Census of Population Subject Reports: American Indians* (Washington, D.C.: U.S. Government Printing Office, 1973).

particularly because technological opportunities may change and because the very nature of reserved rights entails some uncertainty. Furthermore, as the result of a 1983 U.S. Supreme Court decision in *Arizona* v. *California* (1), new concerns have been raised that quantification, once made, may not be changed at a later date to meet redefined needs because developers will have relied on the initial quantification in their investment decisons. On the other hand, some quantification has been urged by both Indian and non-Indian interests to increase certainty for developers.

The Federal role in these issues is complex, and many tribes are finding it increasingly difficult to rely on the Federal Government to act on their behalf. In one role, the Federal Government finances water-storage projects and allocates water supplies from such projects primarily to non-Indians. In another role, the Federal Government acts as public trustee for Indian users. Thus, at any one point in time Federal officials may be representing competing interests: farmers and ranchers v. the Indians. As a result, the Western Indian community has increasingly perceived that its interests are not being fairly and fully represented (15, 21).

Indians defend some claims for water that at present cannot be put to full use. Most of that water would go to agriculture and, in fact, the quantification of Indian rights is predicated on agricultural uses. Legal questions have been raised whether their water rights are restricted to agriculture or can be transferred to nonagricultural and non-Indian uses. Most Indian groups do not have a tradition of, or sufficient resources to begin, large irrigated farms. These problems have been exemplified by the Navajo Indian Irrigation Project, where pressure to quantify water claims preceded clear plans regarding water use (9). In the absence of such planning, Southwestern Indians have considered several options, including the sale of partial allotments to their municipal, industrial, and agricultural competitors.

Other claims—owing to the historical uniqueness of the reservations—focus more specifically on present threats to Indian water use and livelihood from non-Indian development off the reservation. In several areas of the West, non-Indian uses of both surface and ground water off the reservation either have damaged or threaten to damage Indians on the reservation. The Pyramid Lake Paiutes in Nevada, for example, sued the State, the Truckee-Carson Irrigation District, and some 13,000 other water users for lowering the level of the lake so that a principal economic activity, fishing, became unfeasible. The Papago Indians in Arizona have requested a solution to the depletion of reservation ground water supplies by municipal, agricultural, and mining sources, and the Fort McDowell Indians of Arizona objected vigorously to a Bureau of Reclamation plan to build the Orme Dam that would force them to abandon traditional lands. On the Umatilla reservation in Oregon, Indian fishermen lost their fishing rights with the construction of the Dalles Dam on the Columbia River, and have sued to regain them.

Until recently, few incentives have existed for the quantification of Indian water rights. Throughout the history of water-project development, Congress and the executive branch have seldom taken reserved rights into account in development. Both the Colorado River Compact and the Upper Colorado River Compact, for example, are silent on Indian claims to water. The assumption was that such rights would be satisfied within the quantities allocated to each basin and to each State.

Now, increased pressures on existing supplies has brought this issue into sharp focus, in many cases through litigation (table 29). Pursuant to Federal law, States can negotiate for the Federal Government on these matters. Some States (e.g., Utah, Arizona, and Montana) are negotiating with Indian tribes to seek settlement of claims. However, the evidence is not yet available as to whether these experiments will provide equity and fairness to all parties and will avoid future litigation.

Efforts to settle conflicts involving Indian claims have failed, both legislatively and administratively, at the national level. Ironically, Federal mechanisms for participation and

Table 29.—Status of Settlement of Western Indian Claims

This table summarizes the decisional and settlement processes used in the river basins, or sections of basins, where there have been significant clashes between Indian and non-Indian claims to water. A few cases have not matured to the point where the parties have initiated any formal process, and these are omitted from the table.

	Litigation	Regulatory commission proceeding	Administrative decision	Negotiation	Legislation
Arizona:					
Main stem of Colorado River below Hoover Dam	•	—	—	—	—
Lower Colorado River between Grand Canyon and Lake Mead	—	—	—	—	—
Kanab Creek within Lower Colorado River Basin	—	—	—	•	—
Little Colorado River	•	—	—	—	—
Gila River Watershed, except Santa Cruz Basin	•	—	•	•	—
Salt River	•	—	—	—	—
Santa Cruz Basin	•	—	—	•	•
Groundwater Basin in Gila River Basin (Ak-Chin)	—	—	—	—	•
Transbasin diversion from Colorado River to Gila Watershed	•	—	•	—	—
California:					
San Luis Rey River	•	•	—	•	•
White River	—	•	—	—	—
Klamath River	•	•	—	•	•
Colorado:					
Animas, Mancos, Los Pinos, La Plata and other tributaries of San Juan River	•	—	—	•	—
Idaho:					
Rapid River in Salmon River System	•	—	—	•	—
Kootenai River	—	•	—	—	—
Montana:					
Tongue River, Yellowstone Basin	•	—	—	•	—
Big Horn River, Yellowstone Basin	•	—	—	•	—
Milk and St. Mary Systems	•	—	—	•	—
Big Muddy, Poplar, Milk and Missouri Rivers (Fort Peck)	•	—	—	•	—
Flathead River System	•	—	—	—	—
Flathead Lake	•	—	—	—	—
Marias River	•	—	—	—	•
Nevada:					
Groundwater Basin in Walker River Basin	•	—	—	—	—
Owyhee River	—	—	—	•	•
Duckwater Valley and Muddy Creek Basins	—	—	•	—	—
South Fork of Humbolt River	—	—	•	—	—
Truckee and Carson Rivers	•	—	—	•	—
Clear Creek, tributary of Carson River	—	—	—	•	—
New Mexico:					
San Juan River, within Upper Colorado River Basin	•	—	—	—	—
Nambe—Pojoaque—Tesuque River System, tributary of Rio Grande	•	—	—	—	—
Santa Cruz River system and Rio de Truchas, tributaries of Rio Grande	•	—	—	—	—
Rio Grande del Rancho, Rio Pueblo de Taos, Rio Chiuito and other tributaries of Rio Grande	•	—	—	—	—
Chama River and tributaries between El Vado Dam and confluence with Rio Grande	•	—	—	—	—
Bonito, Hondo and Ruidoso Rivers, tributaries of Pecos River	•	—	—	—	—
Santa Clara River, tributary of Rio Grande	•	•	—	—	—
Chaco River, part of San Juan River drainage	•	—	—	•	—
Rio Puerco (west), tributary of Little Colorado River in Lower Colorado Basin	•	—	—	—	—
Rio Grande	—	—	•	—	—
Rio San Jose, within Rio Grande Basin	—	•	—	—	—

Table 29.—Status of Settlement of Western Indian Claims—Continued

	Litigation	Regulatory commission proceeding	Administrative decision	Negotiation	Legislation
Oregon:					
Williamson River in Klamath River Basin	•	—	—	—	—
Umatilla River, tributary of main stem of Columbia	—	—	•	—	—
South Dakota:					
Missouri River and tributaries in western South Dakota	•	—	—	—	—
Lake Andes	•	—	—	—	—
Utah:					
Duchesne River and Tributaries, Green and White Rivers	—	—	—	•	—
Washington:					
Yakima River Basin	•	—	—	•	—
No Name Creek	•	—	—	—	—
Chamokane Creek	•	—	—	—	—
Groundwater Basin (Lummi)	•	—	—	—	—
Skagit River, and tributary, Copper Creek	•	—	—	•	—
White River	•	—	—	—	—
Western Washington rivers containing traditional fishing grounds of tribes signatory to any of five treaties	•	—	—	—	—
Payallup River	•	—	—	—	—
Quinault, Queets and Raft River Systems	•	—	—	—	—
Skokomish River System	—	•	—	—	—
Dungeness, Skagit, Snohomish, Stillaguamish, Pilchuk, Snoqualmie basins, and off-shore sites in Strait of Juan de Fuca and Puget Sound	•	—	•	—	—
Wyoming:					
Big Horn River	•	—	—	—	—

SOURCE: John A. Folk-Williams, "What Indian Water means to the West," *Water in the West*, vol. 1, Sante Fe, Western Network.

negotiation with Indian interests have been severely reduced in recent years. Unless the Federal Government establishes a full commitment to resolve the issues surrounding Federal reserved rights and a focal point for negotiation, uncertainty and confusion for Western development, including Western agriculture, will continue.

Water-Quality Regulation

As noted above, in the 1800's the Federal Government chose to defer to the States on matters of control and development of local water supplies. In the mid-1900's, however, there was a gradual shift back toward more Federal regulatory interest in water. This occurred in the area of water quality, an aspect of Western agricultural water use that affects both the quality of water needed in agriculture and the quality returned to the natural system after agricultural use (see ch. IV).

Federal involvement in water quality control has moved State agencies forward in water-quality regulation. A significant example of Federal action that has had major impact on State programs was the passage of the Federal Water Pollution Control Act of 1972, amended by the Clean Water Act of 1977 (together commonly referred to as the Clean Water Act, Public Law 92-500). Through the combination of two mechanisms, a permit system for point sources of pollution and instream standards of water quality, the U.S. Environmental Protection Agency and the States are obliged to impose restrictions on effluents entering a stream. They are also to undertake steps necessary to ensure that water-quality standards are met.

Nonpoint source pollution, especially from agriculture in the form of salts and agricultural chemicals, received more attention with the passage of the Clean Water Act. Section 208 of that act authorized and directed the Secretary of Agriculture to establish programs to implement "best management practices" on farms and ranches to control nonpoint source pollution from agriculture. Technical assistance and financial support were initially provided. Now, with Federal assistance effectively eliminated, most States rely on voluntary action and cooperation to achieve nonpoint pollution reduction.

Interstate and International Agreements

Interstate and international agreements dealing with Western river systems are important attempts to recognize politically the regional nature of surface water regimes and the need to manage them as total units. Existing agreements define some framework for water use by different parties of interest. At the same time, uncertainty has been created by the potential constraints of some of the provisions as water quality and quantity limits are reached and strict enforcement measures become necessary to ensure compliance. These interstate and international agreements affect all Western water users. As compliance becomes a matter of increased concern, these agreements will influence decisions about the kinds of water-related technology acceptable for meeting compact water quality and quantity obligations effectively. The major Western agreements are noted below.

Interstate Compacts

The major provisions of the *Colorado River Compact of 1922* are (28):

1. It divides the river system into the Upper and Lower Basins and allocates 7.5 million acre-feet per year (maf/yr) to each basin for beneficial consumptive use. The Lower Basin is also given authority to increase its annual use by 1 million acre-feet (maf).
2. It does not recognize a specific obligation to provide water to Mexico. However, a framework is established whereby any future obligation would be shared equally between the Upper and Lower Basins.
3. The Upper Basin is prohibited from reducing the flow at Lee Ferry to below an aggregate of 75 maf in any 10-year period. The Upper Basin is not to withhold water, nor is the Lower Basin to demand water that cannot reasonably be applied to domestic and agricultural uses.

The *Boulder Canyon Project Act of 1928* provided for the construction of Hoover Dam and its powerplant and for the All-American Canal. Its major provisions were:

1. It suggests a specific framework for apportioning the water supplies allocated by the compact of 1922 among the Lower Basin States of California, Arizona, and Nevada. (The States did not adopt this framework, but it was later imposed on them by the Supreme Court decision in *Arizona* v. *California*, 376 U.S. 340 [1964].)
2. It requires California to reduce its annual consumption to 4.4 maf plus not more than half of the surplus water provided to the Lower Basin. (This requirement was met through the California Limitation Act of 1929.)
3. It authorizes the Secretary of the Interior to investigate the feasibility of projects for irrigation, power generation, and other purposes.

In the *Upper Colorado River Basin Compact of 1948* the Upper Basin States apportioned the water allocated under the compact of 1922. The negotiators recognized the problem inherent in allocating water on a strict-quantity basis because of flow fluctuations from year to year. As a result, water was apportioned on a percentage basis to all States except Arizona. Major provisions of the compact are (28):

1. Arizona is guaranteed 50,000 acre-ft/yr. The remaining water is apportioned as follows:
    - Colorado: 51.75 percent
    - New Mexico: 11.25 percent
    - Utah: 23.00 percent
    - Wyoming: 14.00 percent.
2. It recognizes that new reservoirs will be needed to assist the Upper Basin in meeting its delivery obligation to the Lower Basin. The compact provides that charges for

such evaporative losses be distributed among the Upper Basin States. Each State is to be charged in proportion to the fraction of the Upper Basin's water allocation consumed in that State on a yearly basis, and its maximum consumptive use is to be reduced accordingly.

3. It provides for the division of water between pairs of States on a number of specific rivers.

Being in a position to use water available under these compacts has been a problem for some States. For example, the 1922 Colorado River Compact legally guaranteed the State of California 4.4 maf of Colorado River water annually. Yet California has used approximately 5.7 maf every year because it has had the physical structures to convey and use the extra water, while other States have not had this capacity. The Central Arizona Project (CAP), a massive water system which will lift the water almost 2,000 ft in elevation and carry it over 300 miles to make use of Arizona's share, should make its first delivery in 1985 to Phoenix, shifting water away from California users to Arizona users.*

International Agreements

In the *Mexican Water Treaty of 1944-45* the United States promised the Republic of Mexico that 1.5 maf of water will be delivered to Mexico every year through the Colorado River. This provision was part of the negotiations over apportionment of water from the Rio Grande, Tijuana, and Colorado Rivers. The States in the Upper and Lower Colorado Basins were apportioned 7.5 maf for each group of States.

The treaty with Mexico had not been made when the Colorado River Compact was signed. But article III(c) of the compact provides that if the United States recognizes any Mexican rights in the river, these rights would be filled "first from the waters which are surplus over and above the aggregate amount" allotted to the Upper and Lower Basin States (1.5 maf plus whatever the Lower Basin States have been able to use, up to 1 maf/yr).

If the surplus is not adequate to fill the obligation to Mexico, the "burden of such deficiency shall be equally borne by the Upper and Lower Basin . . . ." In short, if the "surplus" waters of the Colorado River are less than 1.5 maf annually, existing rights in the United States could be cut short to make up the difference owed to Mexico. Moreover, under international agreement with Mexico, the quality of the 1.5 maf was to be improved through the Water Salinity Control Project at Yuma, Ariz. (see ch. VII for discussion of desalting techniques).

The *Columbia Treaty of 1964* concluded two decades of study and negotiation by the United States and Canada for joint development of the Columbia River basin. For the United States, large quantities of Canadian storage were acquired to meet certain flood-control objectives in the Northwest States and to provide power through the Bonneville Power transmission system to the Pacific Northwest, California, and to the Southwest. When enacted, its focus was not principally on irrigation, a domestic matter within the concept of multiple-purpose development of U.S. rivers. Eventually, the treaty may restrict the entry of new agricultural users, since such users would have junior rights to existing power rights and hydroelectric power requirements may not be compatible with timing needs of new users. In this sense, hydroelectric power will become a competing use for new irrigation farmers.

Implications for Sustainable Western Agriculture

State and Federal water-law doctrines have helped define general rights and duties. As demands for the limited resource have grown, however, uncertainties have increased about the specific meaning of these rights regarding more intensive water use, potential new users, and opportunities for water transfers and reallocation. A substantial part of the uncertainty concerns the nature of the water right held by an individual. For example, in California, which has attempted to quantify water rights, appropriative rights acquired before 1914 are not required to be recorded. Post-1914 rights were, until 1969, recorded regarding flow rate and seasonal restrictions but omitted total quantities. Even where water rights have been recorded, the quantities of water claimed may be exaggerated, thus largely destroying the utility of the record (12). In addition, uncertainties about the quantities of water involved with Indian and other Federal reserved water rights cloud the titles of many recorded private appropriative rights, and Federal commitment to negotiate and resolve these issues is lacking.

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*For a discussion of the major social, economic, and political issues surrounding the CAP, as well as a physical description of the project, see ref (14).

Problems have also grown regarding the artificial separation of water into legal classes. Surface and ground water rights are administered along different well-established doctrines, as discussed above. Nevertheless, these surface-subsurface waters are connected physically and interact both quantitatively and qualitatively. Rights in atmospheric moisture, a relatively new legal area, are poorly defined because interception technologies are relatively new, although a few States have begun to claim sovereign rights to atmospheric moisture (see ch. VI). If precipitation makes its way to the ground as diffused surface water, the runoff may become subject to other types of water rights before it reaches the streamcourse or ground water. In some States, use of diffused surface water (not yet concentrated in a channel) impounded for certain purposes by a landowner must be secured through special procedures. No State has gone so far as to actually appropriate diffused surface water (26).*

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*For a thorough discussion of the impacts of Federal agricultural production programs on soil and water resource management in general see the OTA assessment: *Impacts of Technology on U.S. Cropland and Rangeland Productivity*, ch. VI, OTA-F-166, August 1982.

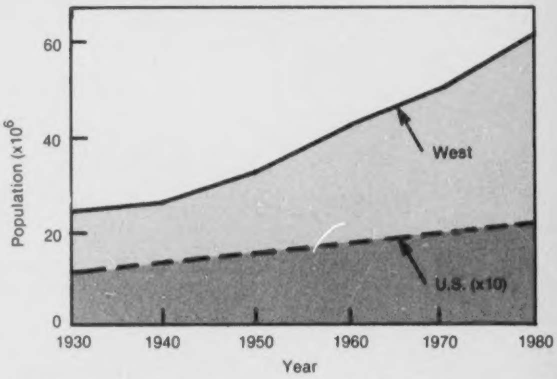
SOCIOECONOMIC FACTORS AFFECTING WESTERN WATER INSTITUTIONS

The social and demographic trends that characterize the West have been shaped by economic opportunities and institutional forces. Such opportunities have been and continue to be conditioned by the distribution and availability of water resources.

Demographics

In many ways, unmanaged population growth constitutes a major long-run threat to agricultural growth and development in the West. People increase demands not only on water supplies but also on space. Since cities grow more easily on level terrain, farmers and urban developers compete for the same valleys. Population increases promote commercial and industrial sectors of the economy, which in turn attract more people in search of jobs. Much of the West is fully involved in this spiral, and local conflicts over land and water use are becoming commonplace.

Figure 29.—Population Rate of Change of the 17 Western States Compared to the U.S. Population, Rate of Change, 1930-80



SOURCE: Office of Technology Assessment staff, from U.S. Department of Commerce, Bureau of the Census, *1980 Census of Population and Housing*, advance reports.

Regional population-growth patterns have shifted in the past three decades. Figure 29 compares the rate of growth for the 17 Western States with that of the entire United States. All four U.S. census regions gained population in each of the intervals between the last three censuses (fig. 30). The Western census region (note that this region does not include all 17 Western States) grew fastest, although its population in-

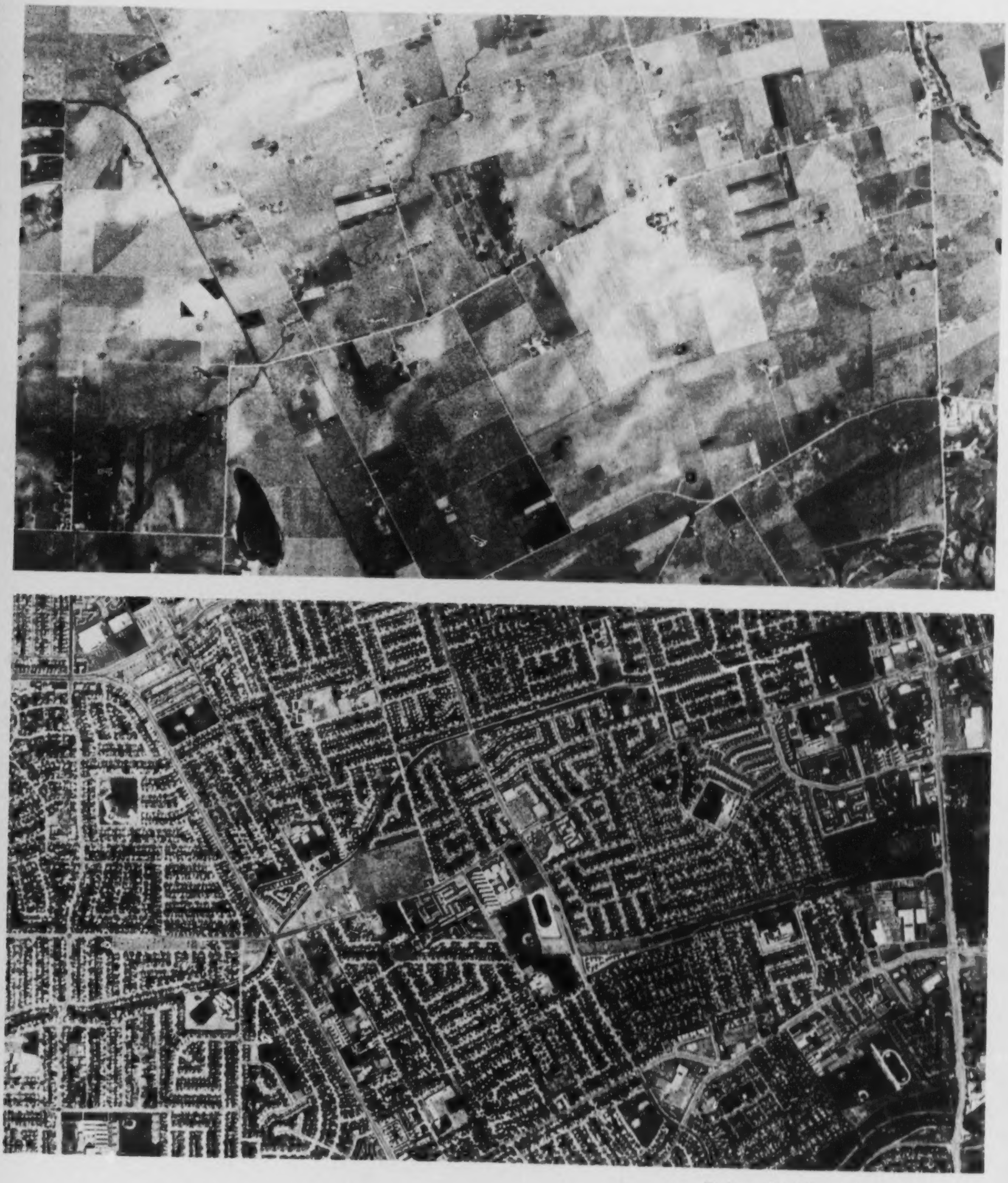
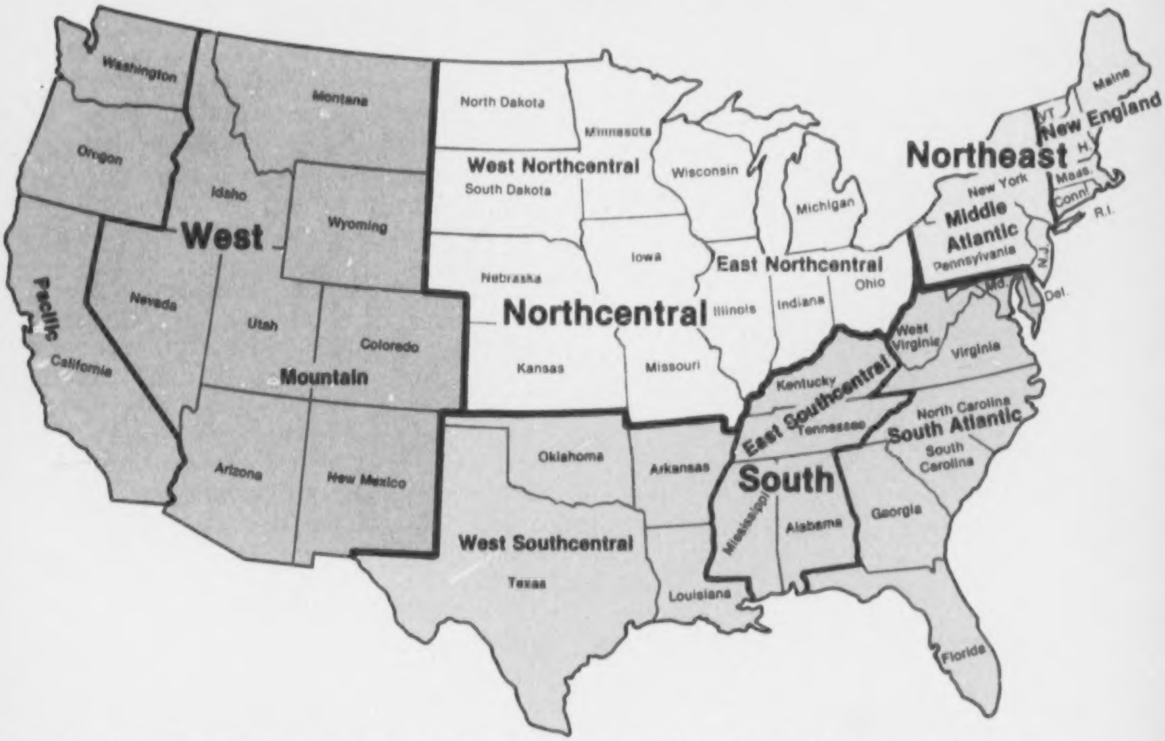


Photo credits: USDA-Soil Conservation Service

Suburban growth of Santa Clara County, Calif., during 28-year period (April 1950 to April 1978). Photo (top shows the area that was predominantly agriculture now covered with highways, housing developments, and industry (bottom)

Figure 30.—United States: Census Regions and Divisions


Washington
Oregon
California
Pacific
West
Idaho
Montana
Wyoming
Nevada
Utah
Colorado
Mountain
Arizona
New Mexico
North Dakota
South Dakota
West Northcentral
Nebraska
Kansas
Minnesota
Iowa
Missouri
Northcentral
Wisconsin
Michigan
Illinois
Indiana
Ohio
East Northcentral
Oklahoma
Texas
West Southcentral
Arkansas
Louisiana
Mississippi
Alabama
Kentucky
Tennessee
East Southcentral
South
West Virginia
Virginia
North Carolina
South Carolina
Georgia
Florida
South Atlantic
Md.
Del.
N.J.
Pennsylvania
New York
Middle Atlantic
Northeast
VT
N.H.
Maine
Mass.
Conn.
R.I.
New England

SOURCE: U.S. Department of Commerce, Bureau of the Census, *Statistical Abstract of the United States 1981* (102d ed.) (Washington, D.C.: 1981).

Components of Population Growth in Regions and Divisions: 1950-80 (numbers in millions)

Regions and divisions	Population 1950	Population 1960	Net migration	Population 1970	Net migration	Population 1980
Northeast	39.5	44.7	+ .3	49.0	+ .3	49.1
New England	9.3	10.5	+ .0	11.8	+ .3	12.3
Middle Atlantic	30.2	34.1	+ .3	37.2	+ .0	36.8
Northcentral	44.5	51.6	– .1	56.6	– .8	58.9
East Northcentral	30.4	36.2	+ .7	40.3	– .2	41.7
West Northcentral	14.1	15.4	– .8	16.3	– .6	17.2
South	47.2	55.0	–1.4	62.8	+ .6	75.3
South Atlantic	21.1	26.0	+ .6	30.7	+1.3	38.9
East Southcentral	11.5	12.0	–1.5	12.8	– .7	14.7
West Southcentral	14.5	17.0	– .6	19.3	– .0	23.7
West	19.6	28.1	+3.8	34.8	+2.9	43.2
Mountain	5.1	6.9	+ .6	8.3	+ .3	11.4
Pacific	14.5	21.2	+3.3	26.5	+2.5	31.8

SOURCES: Bureau of the Census, 1950-70, Revised Estimated of the Population of States and Components of Change, *Current Population Reports* Series P-25, Nos. 3-4 (1965) and 460 (1971). Bureau of the Census, 1970-80, *1980 Census United States Summary Final Population and Housing Unit Counts* (Advance Reports) PHC 80 V-1, 1981, table 1.

crease dropped from 39 percent in the 1950's to 24 percent in the 1970's. The Pacific division within this region grew faster in the 1950's and 1960's, while the Mountain States attracted more population growth in the 1970's (23). State-by-State percentage change in population for the 17 Western States is indicated in table 30.

By 1980, the population of the South and West exceeded that of the two northern regions for the first time. California was the most populous State, with 23.7 million people—far ahead of second-place New York, with 17.6 million (23).

For the period 1970-80, population growth in the West was above the national average with the exception of the Dakotas, Kansas, and Nebraska (table 30). For California, Texas, Arizona, and New Mexico, the increases were dramatic. Since the natural increase in population (births minus deaths) is relatively constant throughout the country, the large total increases in the West have been due to positive net migration: from 1970 to 1976, 623,000 for California; 543,000 for Texas; 356,000 for Arizona; 237,000 for New Mexico; and 1,849,000 for the entire West.

Both push-and-pull factors explain the population flux to the West. Climate certainly carries significant influence. Perhaps equally important is the reluctance of many to endure the inconveniences of city life and the popular perception that Western cities and towns offer a rural-like setting and relaxed lifestyle without a loss of necessary services. Industry seeks what is referred to as "unexportable amenities." A warm, dry climate extends the use-life of capital goods and reduces shutdowns from adverse weather. Also, a growing population of employable persons ensures both a labor force and a demand for manufactured items. Commercial interests respond to urban population changes by developing the service sector. As a consequence, from 1970 to 1977, the West experienced an increase in nonagricultural employment three to four times higher than the national average (table 31). And whereas manufacturing employment in the United States actually declined over the same period, most Western States registered a dramatic increase. The broadening of job opportunities that accompanies the growth of industry and business promotes a regional image of abundant employment, thus drawing larger migrant flows.

Population trends for the 1980's indicate that the population shift to the South and West will continue but will not accelerate as it did in the 1970's. The question is more open, however, regarding the movement to nonurban areas.

Table 30.—Percentage Increases in Population for the 17 Western States and United States, 1930-80

State	1930-40	1940-50	1950-60	1960-70	1970-80
Arizona	14.6	50.1	73.7	36.3	53.1
California	21.7	53.3	48.5	27.1	18.5
Colorado	8.4	18.0	32.4	26.0	30.7
Idaho	17.9	12.1	13.3	6.9	32.4
Kansas	-4.3	5.8	14.3	3.2	5.1
Montana	4.1	5.6	14.2	2.8	13.3
Nebraska	-4.5	0.7	6.5	5.2	5.7
Nevada	21.1	45.2	78.2	71.6	63.5
New Mexico	25.6	28.1	39.6	6.9	27.8
North Dakota	-5.7	-3.5	2.1	-2.2	5.6
Oklahoma	-2.5	-4.4	4.3	9.9	18.2
Oregon	14.2	39.6	16.3	18.3	25.9
South Dakota	-7.2	1.5	4.3	-2.2	3.6
Texas	10.1	20.2	24.2	16.9	27.1
Utah	8.4	25.2	29.3	18.9	37.9
Washington	11.1	37.0	19.9	19.6	21.0
Wyoming	11.2	15.9	13.6	0.6	41.6
17 States	9.2	25.8	29.4	19.4	22.4
Total United States	7.3	14.5	18.5	13.4	11.4

SOURCE: U.S. Department of Commerce, Bureau of the Census, *1980 Census of Population and Housing*, advance reports, from Statistical Abstract '81, p. 10.

Table 31.—Population and Employment Change by Region and State

Regions	Population 1976	Percent change in population 1970-76	Net migration 1970-76 Number	Net migration 1970-76 Percent	Percent change in employment 1970-77 Nonagricultural	Percent change in employment 1970-77 Manufacturing
California	21,510,000	7.8	623,000	3.1	20.6	7.1
Intermountain:						
Idaho	831,000	16.5	64,000	8.9	44.2	29.5
Montana	753,000	8.4	25,000	3.7	21.3	-2.5
Oregon	2,329,000	11.3	159,000	7.6	25.2	10.8
Washington	3,612,000	5.8	64,000	1.9	17.1	3.9
Southwest:						
Arizona	2,270,000	27.9	356,000	20.1	43.7	20.3
Colorado	2,583,000	16.9	237,000	10.7	32.3	18.6
Nevada	610,000	24.8	91,000	18.5	44.5	62.0
New Mexico	1,168,000	14.9	67,000	6.6	37.6	46.6
Utah	1,228,000	15.9	35,000	3.3	32.7	32.7
Northern Plains:						
North Dakota	643,000	4.1	-4,000	-0.6	34.1	4.9
South Dakota	686,000	3.0	-9,000	-1.3	21.1	31.0
Wyoming	390,000	17.4	37,000	11.3	45.9	9.5
Southern Plains:						
Kansas	2,310,000	2.7	-13,000			
				-0.6	25.7	24.2
Nebraska	1,553,000	4.5	11,000	0.8	18.5	5.3
Oklahoma	2,766,000	8.1	107,000	4.2	25.3	19.9
Texas	12,487,000	11.5	543,000	4.9	32.3	17.6
Total United States	214,659,000	5.6	2,857,000	1.4	8.6	-1.3

SOURCE: Finan, et al., 1982. Original source: Bernard L. Weinstein and Robert E., Firestine, *Regional Growth and Decline in the United States* (New York: Praeger Publishers, 1978).

Photo credit: Jack Schneider, ISP

Skyline of Denver, Colo., 1974—a Western metropolis at the hub of growth and urban development

During the first half of the 1970's, one of the major demographic surprises was a reversal of the rural-to-urban population flow, the first time this had occurred since the beginning of the century. This outmigration appears to be to counties adjacent to major metropolitan areas, however, and not to rural counties more removed from urban areas.

A panel of experts assembled by the Population Reference Bureau has projected continued rapid migration to the Mountain States (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming) in the 1980's. While some of this population movement will be related to mining activities, most will be related to resort-retirement growth and suburbanization. According to these experts, "diminishing water supplies will eventually restrain population growth in the West, but not yet in the 1980's" (23). In the meantime, recent population increases in the West are related, for the most part, to nonagricultural activities. Regional water-use priorities that traditionally favored agriculture may be affected by this trend to a more urban/suburban voting population.

Rural Economics and Western Agriculture

In much of the West, as in the rest of the United States, the farm population is comparatively low. Western farm population has dropped to about 3 percent of the total population, close to the 1981 national average (table 32). The ratio of agricultural income to nonagricultural income averages somewhat less than 3 percent in the southern half of the West and 7.5 percent in the Plains area (30). Agriculture itself directly supports a small population; however, as a regional activity it has become an integral part of local economies. Agriculture contributes to such local and regional activities as grain-elevator operation, transportation, and food processing. In Texas, for example, every dollar of farm sales leads to more than $3.40 in the Texas economy (5).

A large, complex economy such as that of the United States is made up of thousands of subeconomies. In the 50 United States, there are over 3,000 counties and approximately 20,000 municipalities, most with populations of less than 2,500 people (3). These small towns are primarily agricultural service centers and are highly dependent on the agriculture that surrounds them.

The irrigation of agricultural areas in the West has changed the productivity of their resources and hence their economic bases. Irrigating large parts of Arizona has changed that

Table 32.—Total and Farm Population of the United States: 1920-81 (numbers in thousands)

Year	Total resident population[a]	Farm population	
		Number of persons[b]	Percent of total population
Current farm definition:			
1981	224,064	5,790	2.6
1980	221,672	6,051	2.7
1979	219,611	6,241	2.8
1978	217,771	6,501	3.0
Previous farm definition:			
1981	224,064	6,942	3.1
1980	221,672	7,241	3.3
1979	219,611	7,553	3.4
1978	217,771	8,005	3.7
1977	215,966	7,806	3.6
1976	214,282	8,253	3.9
1975	212,542	8,864	4.2
1970	203,235	9,712	4.8
1960	179,323	15,635	8.7
1950	150,697	23,048	15.3
1940	131,669	30,547	23.2
1930	122,775	30,529	24.9
1920	105,711	31,974	30.2

[a] Official census counts, except 1975-81, which are estimates.

[b] Farm population estimates for 1920 to 1970 from *Farm Population Estimates, 1910-70,* U.S. Department of Agriculture, Statistical Bulletin No. 523, July 1973; five-quarter averages centered on April beginning 1960. See app. A.

SOURCE: U.S. Department of Commerce, Bureau of Census, "Farm Population of the United States: 1981," November 1982, p. 1.

area from one that produced cattle to an area that produces citrus crops, cotton, and other high-valued commodities. The irrigation of some parts of southern California has permitted that area to switch from essentially no agricultural production to an area that produces many of the Nation's winter vegetables. Irrigating Washington State's Columbia basin has changed that region from extensive cattle grazing to the highly intensive cultivation of hay, sweet corn, and potatoes.

These changes, however, are not made in a vacuum. Once the major change occurs in agriculture, the effects spread to nonfarm parts of the society and the economy. Reactions to change in an economic base are site-specific. A cattle-producing area that suddenly has water to irrigate some of its hay-producing land may not change at all. A desert that is made to produce many labor-intensive crops will change demonstrably. In the latter case, nearby towns—as well as the farms—grow, develop,

Box G.—Economic Impacts of Irrigation on the West

The Grand Valley trade area in western Colorado has been irrigated by Bureau of Reclamation projects for many years. A 1963 study of the area showed that water was used on 3,999 farms (95.9 percent of all farms) and that nearly all of the cropland as well as some of the hay-producing land was irrigated (Struthers, 1963, in Barkley, 1983). In 1960 the 273,000 irrigated acres helped produce agricultural commodities valued at $27.6 million—38 percent of the area's total product. Agriculture was also estimated to be responsible for 18 percent of the "linked" or secondary employment in this area. This amounted to 1,026 persons who produced processing services valued at over $18 million. The analysts responsible for the study also estimated that agriculture was responsible for 7,500 to 10,000 jobs in the general sectors of the local economy. The entire influence of irrigated agriculture is summarized in ratios showing that for each dollar of income originating in agriculture, an additional $1.97 to $2.68 is generated in the local nonfarm sector.

The Columbia Basin Irrigation Project in central Washington was planned almost since the Bureau of Reclamation was formed in 1902 (Corssmit and Barkley, 1975, in Barkley, 1983). The irrigation components of the project became a reality in 1950, and by 1970 over 500,000 acres were irrigated using water supplied by the public project. The land that came under irrigation had previously been of little agricultural value and had been used almost exclusively for grazing cattle and sheep. After two decades of development, the area was reaching economic maturity, which involved massive expenditures by Federal, State, and local governments. By 1970 the Federal Government had invested $6.6 million in nonproject costs in the area (in addition to the direct costs of water delivery), the State and county governments had invested $258 million, and the many local governments had invested $25 million. In addition, utility companies serving the expanding populations invested $198 million. This represents a total investment of $8,032 per capita that was required to install an "appropriate" amount of social overhead capital in the area.

The High Plains area of eastern Colorado began to switch from dryland farming to irrigated farming in the 1960's. The development was carried out by individual farm operators who sunk wells into the Ogallala aquifer. Development was quite rapid. In 1966, 366 wells were registered with the State Ground Water Commission. By 1970, at least 2,000 wells were registered and in use (Rohdy, et al., 1971 in Barkley, 1983). The development occurred in a sparsely populated region and centered on towns that were quite small. The effects of irrigation farming are quite extensive and can be shown as "business multipliers," indicating the increase in nonfarm business that accompanies each dollar of economic activity in irrigated agriculture. The results of a 1973 study show that there was 77 cents of nonfarm business generated for each dollar of economic activity on irrigated farms.

SOURCES: P. Barkley, "The Sustainability of Rural Non-Farm Economics in Water Dependent Agricultural Areas," OTA commissioned paper, 1983.
C. W. Corssmit and P. W. Barkley, "Water Resource Development Related Social Overhead Capital Expenditures in the Columbia Basin 1950-1970," paper presented at the annual meeting of the American Agricultural Economics Association, Columbia, Ohio, 1975. In: Barkley, 1983.
D. D. Rohdy, D. B. Tanner, and P. W. Barkley, "Secondary Economic Effects of Irrigation on the Colorado High Plains," Colorado State University Experiment Station Bulletin 5455, June 1971. In: Barkley, 1983.
Robert E. Struthers, "The Role of Irrigation Development in Community Economic Structures," U.S. Department of the Interior, Bureau of Reclamation, February 1963.

and change. Lifestyles and business patterns are affected. The growth requires the commitment of personal, social, and capital resources that, once put in place, are very hard to move (3).

Because of such investments, the possibility that irrigation may end in some areas of the West is generating increased attention. Irrigated agriculture could be diminished for a number of reasons. The availability of affordable water supplies could change (see ch. X), as in parts of Texas over the Ogallala aquifer, or competition could cause water to be shifted from agricultural to other users who can pay more, as in parts of Arizona and Colorado. Similarly, irrigation could damage the soil with salt buildup over time (see ch. VIII) to the degree that some areas cannot be economically farmed, as in parts of New Mexico and California.

Where competition diminishes agricultural use of water (e.g., when large energy companies buy major water rights), the economy of the area may remain strong even though particular patterns of community life and business may be changed as shifts take place away from an agricultural to an industrial/mining economy. Such change may have serious and in some cases negative social effects (even with the emergence of a stronger economy) on others in the local community who may not have chosen to elect that change. Other areas may be able to remain in irrigated agriculture only with large subsidies in water or energy. Thus, social costs are also incurred, this time by the taxpayer.

These varying consequences underscore the importance of taking into account short- and long-term effects on local farm and nonfarm economies of public investments made in Western water use and agriculture. The question increasingly asked is whether new investments can generate a sustainable Western agriculture that is relatively stable for social and economic growth over the long term or whether the investments will be more productive in another sector of the economy.

Competition for Western Water

Water supplies can be used to support farming, mining, industry, urbanization, or combinations of these activities. The socioeconomic character of a region is influenced substantially by which of these activities enjoys the greatest relative control over water resources. Traditionally, agriculture has been dominant in establishing and maintaining the particular flavor of Western living and, to a large extent, has defined the economic, political, and cultural legacy of the region (11). In the past, federally subsidized water has placed irrigated agriculture in a favorable competitive position with other uses of water. Changes in Federal funding policies may affect the competitive advantage of irrigated agriculture and have ramifications for future agricultural production and the kinds of water-related technologies attractive to the producer. As Western populations expand in nonfarm sectors, greater demand is placed on land and water resources formerly used by farmers and ranchers (table 33). Decisions about who will get water may increasingly be affected by the "value" or "cost" of the water and by which competing users will be willing and able to pay. Major competitors for Western water are noted below.

Western Indians

As discussed in detail earlier in this chapter, some Indian claims are being defended in agricultural and nonagricultural uses, including instream uses such as fishing. The American Indian is a potentially large group of competitors. While quantification of many of their claims is unsettled, the potential impact of the amounts involved on all other existing rights created after the establishment of their reservations is substantial.

Energy and Mining Uses

One of the largest industrial developments affecting recent water policy in the arid/semiarid region is the growth of the energy industry (2). Although the west coast and other urban centers have developed a diversified manufac-

Table 33.—Projections of Changes in Total Cropland and Irrigated Farmland by State, 1975-2000

	Change in percent of cropland		Acres of irrigation farmland (1000 acres)		
Regions	1975-1985	1985-2000	1975	1985	2000
California	-2%	-5%	8,495	9,132	9,854
Intermountain:					
Idaho	+1%	-1%	2,989	3,351	3,400
Montana	+1%	+1%	2,010	2,967	2,904
Oregon	-1%	-1%	1,742	1,987	2,096
Washington	+1%	-1%	1,421	1,809	2,013
Southwest:					
Arizona	-3%	-6%	1,207	1,112	1,057
Colorado	+1%	+1%	3,313	3,156	3,375
Nevada	39%	38%	828	737	773
New Mexico	-1%	-1%	956	877	816
Utah	1%	+1%	1,056	979	1,062
Northern Plains:					
North Dakota	+1%	+1%	94	126	230
South Dakota	-1%	-2%	218	274	380
Wyoming	2%	1%	1,731	1,818	1,874
Southern Plains:					
Kansas	7%	8%	2,044	2,618	2,823
Nebraska	+1%	+1%	4,315	4,858	5,118
Oklahoma	+1%	1%	566	580	589
Texas	+1%	-1%	7,414	6,886	6,170

SOURCE: Finan, et al., 1982. Original source: U.S. Water Resources Council, *The Nation's Water Resources, 1975-2000*, vol. 2, pt. III, table III-29, 1978.

turing sector, energy development has been the principal industrial force in such areas as the northern Great Plains and Rocky Mountain States, and both boom towns and company towns dot Western maps. The relatively recent surge of the energy industry, particularly coal and oil-shale mining, has brought increased economic opportunities to many Western areas.

Most estimates of demand for water for energy production, slurry-line transportation, and cooling purposes conclude that energy demand for water on a regional scale is relatively small compared with that of irrigated agriculture. However, on a site-specific basis, increased water use to meet energy demand in such areas as the Rocky Mountain States will have a significant impact on the availability of water for other purposes, especially for agriculture (18). Ultimately, the quantities of water "required" for energy production at a particular site will be affected by the cost the producing industry must pay for that water and associated restrictions put on its use (see ch. III). Much of the future of energy production in the West hinges on the ability of energy-producing firms to bid water away from irrigated agriculture (16) (see discussion in app. C on the value of water in alternative uses).

The competition for water between farms and mines also raises arguments over the desirability of development paths and the kinds of practices used by each. As extractive operations, mines are limited by the quantity, quality, and world price for mineral products, and the rise and fall of boom towns underscore the cyclical nature of this activity. Mining operations use land and water as short-run inputs and with full awareness of their eventual deg-

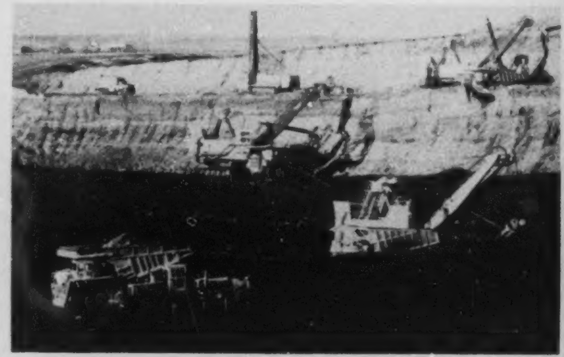


Photo credit: © Ted Spiegel, 1982

Mining Wyoming soft coal. Proposals to transport in slurry pipelines to Eastern markets would require extensive offstream water resources radation or depletion. Farms and ranches may be perceived to use land and water on a more permanent and beneficial basis; however, some present Western agricultural practices are degrading land and water both (see e.g., chs. VI, VIII, and X).

Municipal and Other Industrial Uses

Municipalities and nonmining industries use a relatively small fraction of the total amount of water used in the West. In table 34 this fraction is compared with agricultural use for some States of the West. Municipal and industrial water users are in a relatively favorable position with respect to future water supplies, owing to their superior financial capacity. In many areas, municipalities have developed reliable supplies of water and have supplemented these supplies by water from public projects. As compared with some agricultural users, they are accustomed to paying at a level closer to full cost of development, transportation, and purification. Federal law—and State law in States such as California—requires municipal and industrial users to pay their fully allotted costs. Costs may rise substantially, but urban and industrial water users will probably make minor financial or lifestyle adjustments to accommodate these changes.

Municipal and industrial users are increasingly interested in future water policy, particularly with respect to new water-development projects. Some communities still see growth as both a likely and desirable trend and foresee the need for additional water to permit such growth to occur. Municipal and industrial leaders fear drastic shortages such as those in the severe drought of 1977-78. The efforts of southern Californians to promote the Peripheral Canal and its accompanying works are evidence of this concern for seeking a margin of safety in drought situations.

Moreover, surface water diversions used to develop additional irrigated acres may increasingly compete with opportunities to develop hydropower for municipalities and industry. Whittlesey, et al. (33), studied the economics surrounding the irrigation/hydropower tradeoff the Pacific Northwest and concluded that, using present low values for irrigation water, most new irrigation developments in the Pacific Northwest represent a net loss for the economy of that region. Instead water use is heavily weighted in favor of hydropower generation because of the tremendous power-producing potential of the many dams on the Columbia River.

Resource Protection Uses

Agriculture must face competition and constraints on water use from interests concerned with environmental protection and resource conservation. Such interests have been successful in limiting access to new sources of water by placing some water sources in a protected status—e.g., in the wilderness and scenic rivers classification. The requirements for minimum streamflow standards have placed a new limitation on consumptive use (see ch. III).

In those areas where underground aquifers are being "mined," as in Arizona and the Central Valley of California, pressure exists to impose limitations on the levels and rates of withdrawals and thus reach a sustainable balance

Table 34.—Rate of Change in Water Use as Percentage of Total Water Use, Municipal and Industrial (M&I) v. Irrigation (Irrig.) Purpose in Selected States

	1955	1960	1965	1970	1975	1980
Arizona (M&I)	3%	4%	6%	8%	10%	10%
(Irrig.)	96%	94%	94%	93%	90%	89%
North Dakota (M&I)	63%	30%	39%	65%	78%	74%
(Irrig.)	30%	49%	45%	29%	18%	21%
California (M&I)	25%	41%	40%	30%	30%	30%
(Irrig.)	75%	58%	60%	69%	69%	69%
Texas (M&I)	39%	38%	41%	60%	57%	58%
(irrig.)	59%	59%	56%	37%	41%	40%
Nebraska (M&I)	22%	27%	20%	20%	14%	91%
(Irrig.)	77%	69%	78%	78%	78%	78%

SOURCE: U.S. Government Survey, *Estimated Use of Water in the United States*, publications for 1955-80 (Washington, D.C.: U.S. Government Printing Office, 1955-80).

Photo credit: USDA-Soil Conservation Service

Idaho wilderness, an example of water resources in a natural state. Here, beaver dams provide natural water control

between extraction and recharge. In Arizona, this pressure—largely from urban and industrial interests—has already resulted in legislation that will impose a "duty of water" on agriculture—in effect, a limitation on the quantities of water that may be used in growing various kinds of crops. The director of the Arizona Department of Water Resources has been given extraordinary authority to define the limitations under which water may be used and powerful tools of enforcement to achieve these legislative ends (see app. C). Other Western States (e.g., Colorado and New Mexico) have specific statutory policies authorizing the mining of those ground water acquifers with little or no natural recharge capacity

Resource protection issues have broad implications for the West. Traditional water use and development relationships have been substantially altered in recent years by a broadening of interests related to water resources and changing institutional goals with respect to Western water development. At the national level, environmental values have gradually gained a more prominent level among public priorities. The relative primacy of Federal development agencies such as the Bureau of Reclamation has been challenged. Legislation has been enacted to strengthen the role of other agencies or to create new agencies, such as the Environmental Protection Agency. These policy developments have altered the missions of traditional agencies by placing them in the context of a broader decisionmaking structure. A most notable example is the passage of the National Environmental Policy Act (Public Law 91-190), which requires Federal agencies to prepare environmental impact statements prior to undertaking new projects. Support at the local level has grown for retaining water resources in a natural state. In addition, the traditional sentiment that "development" (inferring "growth" in quantity) is a positive value is no longer uniformly held. Indeed, major new water-project developments may increasingly encounter significant opposition and competition from distinct elements of the general public.

THE ECONOMICS OF WESTERN WATER

The market system allows property to be bought and sold, and thus transferred between uses and users. It forms the basis of the economic system in the United States and as such can be subsumed under the general heading of economics and, with respect to water, the economics of Western water.

A market depends on the rights of ownership and the legal conditions for exchange. The owner of a good as simple as a pitchfork has complete rights to that pitchfork and can sell it to a neighbor. Rights of ownership transfer with the sale. The pitchfork will be sold if its present owner feels the value of the money obtained in exchange equals or exceeds the value of the pitchfork. All well-functioning markets operate in this fashion. Exclusive goods—goods that have well-defined and perfected rights attached to them—are exchanged whenever dispositions about their relative values differ.

If rights in water were as straightforward and secure as rights in pitchforks (or even rights in land), a highly developed and organized water market would emerge. Irrigators would purchase water from industries if irrigated crops were worth more to farmers than water for cooling or dilution was worth to industrialists. Public utilities would purchase water from householders if the value in power generation was higher than the value of water for green lawns and kitchen gardens. Wheat farmers would purchase irrigation water from corn farmers if the value of wheat exceeded the value of corn by an amount sufficient to make the transaction worthwhile.

A Market for Water

Although there are some areas where the market does allocate water among uses and/or users, market exchanges of water are not the rule. Attempts have been characterized as "rudimentary" and unorganized (4). An important exception is found in the Colorado-Big Thompson project area of northeastern Colorado, where a relatively sophisticated market has evolved (see app. C).

Valid reasons exist for the lack of water markets. Many derive from legal and institutional factors affecting water use and exchange that have evolved in the West, as discussed earlier in this chapter. The appropriations doctrine assumes a sequence through time. "Prior rights" for a particular use may impede an individual's ability or desire to sell. The doctrine of beneficial use may establish a hierarchy of uses inconsistent with water moving to its most economical use. The riparian doctrine and the doctrines of correlative rights tie water to other resources or to a particular geographic territory and impede its transfer to other uses and users.

Other factors that hinder the formation of an orderly market for water include the physical characteristics of water, its variety of uses, water's use as a public good, external or third-party dependence on water, and the recent emergence of water as a scarce, and hence "economic," factor of production (34). The difficulties associated with measuring use, location, and quality compound the problem of identifying water, assigning rights to it, and selling it in an orderly market.

Physical Characteristics

The physical barriers to establishing a water market stem from the fact that water changes its form and location as it passes through the water cycle. Water changes from solid to liquid to gas and moves from high locations to low locations. Because it is difficult to identify specific units of water, the ability to assign and enforce property rights is more limited than a well-functioning market might require. Assigning clear title to atmospheric moisture may, for example, interfere with assigning rights to subsequent rainfall. Also, most water users consume only a part of the water that comes to them. Water used to generate hydroelectric power may not be diminished (consumed) in the process but will be moved in location. Even water that is allocated to irrigation is not entirely consumed by plants; some seeps back into the water channel as return flow. Often the returning water picks up soluble salts and other chemicals as it moves through soil and back into streams. Thus, the return flow is lower in quality than the water originally applied by the irrigator; it is now a different commodity.

Multiple Uses

Some water is, and can only be used for a single purpose. A farmer whose remote windmill pumps water for a flock of sheep is pumping single-purpose water. A municipality pumps potable water to residential areas, and much of this is not available for reuse at a later time or in another plan. That portion of irrigation water consumed by growing plants cannot be recaptured for a second use. Many of the major uses of water, however, are not consumptive uses and require only that water be relocated or prevented from being relocated. Recreation is a good example. Water flowing through swift mountain streams or impounded in the lake behind a major dam is used for swimming, boating, fishing, and for its esthetic appeal. The same water may be released in order to generate electricity or maintain the flow of a stream. While it is conceivable that power users could organize and offer a price for water used in generating electricity, it is impractical to think of swimmers organizing in order to purchase the "swimming rights" that go along with a major water impoundment. The major (and minor) users of water have *interests* in water, but no identifiable and merchantable rights. Thus, the market fails to allocate properly the water used for several purposes.

Public Goods

A public good (sometimes referred to as a collective good) is a good that can be used "within reasonable limits" simultaneously by many people. More than this, no one person's use detracts from the quantity available for other people to enjoy. A city park is a public good. One person can use it without reducing the amount of park-use time available to a second, third, or tenth person. Many water uses have public goods characteristics. Recreation is one example, navigation is a second (another boat can go up the Columbia River), and flood protection, which is not a water use but is a kind of water control that inhibits other uses, has public goods characteristics.

Public goods are hard to value and hard to price. One user may know that his/her use has value and will bring an increase in utility, but that user also knows that if someone else will pay the bill, he/she can get the good for free. The user will then be what is called a free rider. Water-resource management is full of free-ride problems, all of which contribute to the difficulty of organizing a well-balanced market in which water can be purchased by potential users and sold by those who no longer have use for the resource.

External Effects

In economic terms, "externalities" are unintended consequences of an exchange or a production process. Some, such as the black-lung disease suffered by thousands of coal miners, are quite harmful. Others, such as the social benefits stemming from an educated populace, are valuable. All have one characteristic: if the primary economic activity is altered, the external effects are altered, too. Water use is filled with externalities. Towns grow up around irrigation projects. Aluminum is smelted near hydropower dams. Marinas are installed near reservoirs. Owners and participants of these external activities eventually develop a vested interest in the present allocation of water and can act to impede the orderly functioning of a market. Alternatively, the *possibility* of large beneficial external effects may lead some industries or groups of individuals to ask for water reallocations that are not consistent with the highest and best economic use of the resource.

Recent Emergence of Scarcity

While the idea seems anachronistic, the true economic scarcity of water is a relatively new phenomenon in the arid West. Most crop-related agriculture in the West is enhanced by irrigation. In early years, water was known to be available, but large expenditures of capital and labor were required to move it from mountains and rivers to arable land. The market, then, was not for water but for the other resources needed to convey water. No market was needed; there was generally enough water for all reasonable uses.

These complexities—the physical characteristics of water, the multiple-use problem, water as a public good, external effects, and the recent emergence of water as a scarce resource—have impeded the organization and development of a well-functioning market. Even though a market may help water allocation among uses and users, no general market has emerged. However, few economists will argue against a market for water. An organized way of trading or exchanging rights to this resource could help ensure that the net social product accruing from use of the resource would increase. This option has received increased attention at the State level and within some Federal agencies.

Proponents of a market argue that if a market does not exist, allocation of water will be left to a governmental entity. Values will have to be set so that priority of use can be established to determine who will use the limited supplies and government will do this through the political or legislative system instead of the market system (see, e.g., Arizona's legislative approach to ground water reallocation, app. C). According to these proponents, government intervention has historically failed, especially when trying to "correct" market failure; therefore, the market system should be given an increased opportunity to participate in the water allocation process. At the same time, a need for special mechanisms and safeguards to protect third parties and address other issues peculiar to water is generally recognized.

Water Economics in a Nonmarket Setting

Economics and economic reasoning play an important role in the water-allocation decisions made by individuals, groups of users, and governments. These decisionmakers often use surrogate or artificial prices to help guide decisions about who will have access to water and how it will be used. In the absence of freely operating markets, the government has often been the decisionmaker and has established regulations to guide water use. Many decisions are reached only after determinations of the value of water have been made and after these values have been processed through an analytical process known as benefit-cost (or, frequently, cost-benefit) analysis.

Water Value

The economic value of water is relevant only when explicit recognition is given to quantity, location, quality, and time of supply of the water that is being evaluated—i.e., the hydrologic system must be considered in terms of its interactions with climate, land, ecosystems, and pertinent social and economic systems. This intricate set of relationships is further complicated by the highly variable nature of water supplies and the importance of sequential uses (multiple uses) of water as it flows from upper watersheds to its eventual destination in the sea or freshwater system. The value of water is highly site-specific and varies directly with local conditions of supply and demand for the resource in a particular use. Even though these supply and demand conditions do not often work themselves out in a market setting, they form the basis for evaluations using surrogate prices.

Benefit-Cost Analysis

Nonmarket resource-allocation decisions can be made by using benefit-cost analysis (22). Water-resource planning and decisionmaking, in fact, represent two of the initial practical applications of benefit-cost analysis, and water may still be the resource most widely allocated on the basis of benefit-cost evaluations.

The benefit-cost framework is based on the same principles found in any well-functioning market system. It assumes consumer sovereignty and accepts the existing distribution of purchasing power as given. The main analytical problem posed by this method is derivation of a set of prices that are close estimates of undistorted market values when there is no clear and well-articulated market value for the reource. Once determined, these prices can be used as a guide in many water-allocation decisions.

The process of estimating water values uses the concept of *willingness to pay* as a basic indicator of economic value. Willingness to pay reflects the dollar amount that a rational, fully informed consumer would be willing to spend in lieu of doing without the commodity or service. Willingness to pay for water is the maximum amount a farmer would be willing to pay for an extra acre-foot of irrigation water or the maximum amount a group of fishing enthusiasts would be willing to pay to keep water flowing in a mountain stream.

Varying from one water use to another, willingness to pay has an important influence on demand for water. Some uses for water are very intense, and people are willing to pay high prices to satisfy this need. People are less inclined to pay high prices for less intense uses of water. Household water falls into the former group; water for boating falls into the latter. Willingness to pay for water is also very reponsive to the quantity supplied. A household can use only a given amount of water for cooking, washing, and watering the lawn. If more is made available, willingness to pay for the added water falls rapidly to low levels. Once a crop has received "enough" irrigation water, additional water may have a negative value. In formal terms, significant increases in the supply of water for a particular use will have a negative effect on the price (or value) of water at the margin.

Methods of Valuing Water

A number of methods and conceptual bases can be used to generate estimated prices for water (boxes H and I). No method is correct or incorrect in the abstract. A particular method may be better or worse for a specific purpose. Many methods are correct or acceptable in the restricted context of a local- or private-planning decision but have limited applicability in valuing water from a national, long-term policy perspective. This is because once a method is chosen, it may yield different values for water at different sites, depending on what is being done with the water, when, and how.

Many estimates of water values appear in both popular and technical literature. The range of the empirical results demonstrates the problems of trying to place values on water for national water planning and policymaking. One of the most complex problems is assigning values that are comparable in concept, place, form, and time. The numbers below summarize the results of a range of available contemporary studies on water values. The estimates are for 1acre-ft of water devoted to a given use in a particular year. This type of estimate is often referred to as a point estimate, since it considers only the primary value of water at a single point within a limited (given) period in time. The studies from which these numbers are taken are discussed in more detail in appendix C.

The range of point-value estimates for Western, consumptive uses is (34):

In agriculture	$7 to $80/acre-ft
In industry	$0 to $1,600/acre-ft
In domestic use	$150 to $250/acre-ft

Box H.— Estimating Water Prices for Use in National Policy: An Overview of Methods

Since the market does not price water directly, economists have developed several methods to estimate water values:

- *Ex post statistical analysis of water-user behavior.*—This method applies conventional statistical analysis to water-consumption patterns of various users. It has an advantage over some other techniques in that it relies on actual willingness to pay for water.
- *Change in net income.*—This procedure defines the value of water as the incremental addition to profits arising from an incremental application of water. Its results are somewhat deceiving and often incorrectly applied.
- *Alternative cost.*—Water is valued as costs saved by employing a water-intensive production plan rather than the most economically reasonable labor- and capital-intensive producing plan. This approach is sensitive to assumptions about such factors as technology and interest rates.
- *Direct observation of markets.*—This technique is rarely available or suitable for water-policy analysis because of limited reliable markets.
- *Consumer surveys.*—The value of water is calculated by asking consumers to place values on changes in water supply or quality for certain public goods such as recreation or pollution abatement. Estimates are potentially useful, but not always perfect substitutes for price.

SOURCE: R. Young, "Allocating the Water Resource: Market Systems and the Economic Value of Water," OTA commissioned paper, 1982.

Box I.—Economic Theory and Its Realization: Some Technical Problems in Setting Water Values

Economic methods that estimate the value of water are designed to establish an artificial but useful price for water in a particular use, at a particular site, and at a given time. The various approaches depend on the concept of *ceteris paribus,* which means that other economic variables are kept equal while the price of water is estimated. Although useful conceptually, these methods are subject to several limitations, noted below:

- *Indirect effects resulting from water development.*—When major water developments occur, other economic changes are generated at local, regional, and national levels. Water values should be adjusted to reflect these perspectives.
- *Marginal v. total value.*—Like other inputs in crop production (e.g., labor and fertilizer), the value of water is its contribution to output. In setting water prices, the incremental use of water and its effect on net product should be evaluated in lieu of weighing total water costs against total output.
- *Changing water values during crop-production cycle.*—The value of agricultural water varies during the crop-production cycle. Emergency, short-term values, for example, are generally higher than prices estimated for long periods of time. During a drought, a farmer may be willing to pay a high price for water. Conversely, if rainfall is plentiful or if the farmer chooses not to plant a crop, the value of water is lower.
- *Comparing values in place, form, and time.*—Water is a bulky commodity that may need to be transported, treated, or stored before used. The investments needed to carry on these processes should be considered in the water-valuation process.
- *Measuring quantity: water diverted or water consumed.*—Obviously, the quantity of water supplied is an important determinant of its cost. However, large differences in price will result, depending on whether water values are calculated by the amount of water that is withdrawn or whether water consumption rather than diversion is considered. No set rules or conventions exist.
- *Annual rental value or future income.*—Where a water user rents water annually, the value of the water is limited to the rental payment. If, however, the user owns the water and has a water right, its value is usually much higher and consists of its present value and its future expected annual value. To reconcile these two concepts, interest rates and annual returns should be considered in setting water values.

SOURCE: R. Young, "Allocating the Water Resource: Market Systems and the Economic Value of Water," OTA commissioned paper, 1982.

The range of point-value estimates for Western, nonconsumptive, instream uses is (34):

Hydropower generation	$3.30 to $30/acre-ft
Waste-load dilution	$1.30 to $15/acre-ft
Recreation	$2.00 to $13/acre-ft
Fish habitat	Less than $1/acre-ft
Navigation	No acceptable estimate

Figures as varied as those above make it difficult to place a "true" value on this resource and illustrate their limited use in evaluating national water policy. Instream use values pose a special set of problems. While economic analysis and accounting procedures can be used to value the products of instream uses, such as hydroelectric power, it is difficult to develop adequate values for the public uses (public goods) of the water. This problem has become more serious with the passage of time. Many people now want to use water for such public uses as recreation, boating, waste dilution, and esthetic charm. However, the market does not provide access to values for these uses, and analysts have not been entirely successful in developing surrogate values. The value of water in instream uses is very hard to determine because of:

1. public goods problems associated with many instream uses,

2. multiple-use problems, and
3. a lengthy national water policy tradition that assumes that water used for hydropower and water used for navigation should be free (34).

Economic Efficiency and the Adoption of Water-Related Agricultural Technology

Agricultural and nonagricultural users respond to economic conditions in their attempts to become efficient. A farm unit will be economically efficient when it maximizes its profits (13). Efficiency occurs in relation to a number of factors affecting farm operations. In the last 20 years, new irrigation and engineering technologies have led to increased engineering and economic efficiencies in irrigation. In almost all cases, the purpose of such technology has been to conserve nonwater inputs—principally energy and labor. In other words, becoming economically efficient in irrigation may or may not have saved water. In most areas the actual conservation of water has been a byproduct of shifts in the production system caused by changes in the relative prices of inputs (19).

This is not surprising, given the artificially low price that most irrigators pay for water. Even in the case of the Ogallala aquifer, increased pumping costs, not increased water prices, have been responsible for the increased marginal cost of water to a user. Also, subsidies have reduced the cost of water to some users and thus the amount the user could gain in the sale of that water. This has allowed the levels of demand for water to remain relatively high and the incentive to sell for economic gain relatively low. When water subsidies occur, water use may be economically efficient from the point of view of the individual user, but it will not be efficient from society's point of view, since society (the subsidizer) pays some of the individual's costs.

Changes in Prices Paid for Nonwater Inputs

Irrigated crop production is an energy-intensive activity in which the cost per unit of output is greater than it is for dryland production in the same locale. The irrigation farmer is thus very sensitive to energy prices. Table 35 indicates expected pumping costs per acre-foot of water, assuming a number of alternative energy prices and water depths. Since the 1960's, the price of natural gas has risen from some $0.50 per thousand cubic feet to over $3 per thousand cubic feet—a sixfold increase in pumping costs. In the 1960's, it cost $6.07 to lift an acre-foot of water 250 ft. By the early 1980's, the cost for the same lift was $36.49 per acre-foot.

Table 35.—Cost per Acre-Foot of Water to Pump at Alternative Depths, Given Selected Natural Gas and Electricity Prices

Depth (ft)	Energy use[a]		Natural gas price ($/000 ft^3)					Electricity price (¢/kWh)			
	Natural gas (000 ft^3)	Electricity (kWh)	0.50	1.00	1.50	3.00	5.00	0.01	0.03	0.05	0.10
			$/acre-ft								
50	5.36	154.2	2.68	5.36	8.04	16.09	26.81	1.54	4.62	7.70	15.40
100	7.05	259.6	3.53	7.05	10.58	21.16	35.27	2.60	7.80	13.00	26.00
150	8.75	265.1	4.37	8.75	13.12	26.24	43.73	3.65	10.95	18.75	36.50
200	10.44	470.5	5.22	10.44	15.66	31.31	52.19	4.71	14.13	23.55	47.10
250	12.13	580.0	6.07	12.13	18.20	36.39	60.66	5.80	17.40	29.00	58.00
300	13.82	681.4	6.91	13.82	20.74	41.47	69.12	6.81	20.43	34.05	58.10
350	15.52	786.9	7.76	15.52	23.27	46.55	77.58	7.87	23.61	39.35	78.70
400	17.21	892.3	8.60	17.21	25.81	51.62	86.04	8.92	26.76	44.60	89.20

[a] Calculated based on equations in D. Kletke, R. Thomas, and Harry P. Mapp, Jr., "Oklahoma State University Irrigation Cost Program, User Reference Manual," Oklahoma State University, Department of Agricultural Economics Research Report P-770, 1978. Pressure was assumed to be 45 pounds per square inch (PSI) and pumping efficiency with natural gas 65 percent.

SOURCE: R. Lacewell, "Economic Efficiency of Agricultural Water Use in the West," OTA commissioned paper, 1982.

The overall effect of rising energy costs on irrigation from ground water sources cannot be determined from general estimates. Higher pumping costs will probably mean less pumping and therefore less irrigation. Specific results depend on the nature of the aquifer, relative crop prices, and prices of other inputs. Nevertheless, as the cost of pumping water increases relative to crop prices, there is an economic incentive to apply less water per acre of the crop.

In some areas, rising energy costs have severely affected irrigated agriculture. A 450-percent increase in natural gas prices between 1972 and 1975 caused cotton production to diminish from 200,000 acres to 20,000 acres in the Trans Pecos area of Texas (5). On the whole, however, energy price increases are not projected to have such dramatic effects on cropping patterns (16).

Other input costs may affect the adoption of water-related agricultural technologies as well. In the late 1960's and 1970's, for example, use of sprinkler systems expanded significantly in the Western United States. This shift to a new technology for applying water was seldom made for the purpose of "saving water." Existing gravity-flow irrigation systems were often converted to sprinkler systems in order to save labor, as well as energy. In some cases, sprinkler rather than gravity-flow irrigation systems were installed to ensure either the efficient use of inputs such as chemical fertilizers or the use of a highly sophisticated and intensive farming system (19).

Increased costs of inputs relative to crop and livestock prices have implications for the structure of irrigated agriculture in the West in that they will reduce net farm income per unit of land. Thus, each farmer who maintains present agricultural practices may require more land to maintain a given level of living, suggesting the need for larger farms. Irrigation may not disappear from the West over the next few decades, but the organization and structure of irrigated farming is likely to undergo continual adjustment.

Changes in Prices Received

Profitability of irrigation is affected as much by crop prices as by input costs. The level of demand for water will be influenced by the amount of crop in production and by the prices received and expected for the crop. As crop prices increase, potential profits will increase, motivating the producer to plant more acreage which in turn will increase the consumptive use of water, assuming no increased prices for the water. If significant increases occur in any combination of actual water prices, delivery costs, application costs, and perceived user costs for water, crop prices received can have a significant impact on the demand for water.

Moreover, if real prices for crops decline, there will probably be some loss of irrigated acreage. Even though the impact of crop prices on the economic viability of irrigated agriculture may be as important as costs of production, there is one main difference: an individual farm cannot influence crop prices, whereas an individual farmer may be able to have some influence on costs of production by manipulating technologies and improving management.

It is likely that changes in relative prices and availability of nonwater inputs will continue to influence the adoption of new technology for water application. To foresee the impact of new water-application technology on water use, it will be necessary to have a sound understanding of the farming system. Predictions about water use cannot be made by concentrating on the single input of irrigation water, and public policies that ignore this fact can be successful only as long as there is plenty of water to meet the demands for water. Once water becomes more scarce relative to demand, perceived costs to the water user will have to increase to maintain a socially efficient rate of water use. The rate of water use will be determined by the entire farming system and will involve the adjustment of rates of use for many inputs in addition to the cost of water.

CONCLUSIONS

Decisions about water rights and their administration have developed along political boundaries, usually the State unit. Water law has developed to solve particular problems on a sector-by-sector basis. For example, traditional Western water law was designed first to ensure miners a water supply. Then agriculture became the dominant sector of interest, greatly influencing the law's growth. In the early 1900's, municipal and industrial users were granted certain rights under law. In the 1960's and 1970's, water-quality programs were developed. As a result, application of traditional water law has raised difficulties among users and among States sharing a common body of surface or ground water. It has also made water planning and management problems more severe as it developed without regard to natural resource boundaries.

Markets for Western water have been slow to develop. A number of reasons related to the physical nature of the resource, public goods characteristics, externalities, perceived absence of scarcity, and social values have been the cause. Allocations of water are made through complex sets of institutions, legal restrictions, and government regulations. While these provide order and regularity to the delivery of water, they do not always encourage or allow water to be put to its best use for the general public interest.

Economics and economists play a central role in evaluating water and water projects. They use a number of tools to make determinations of the price or value of water. These tools are very specific, and each can yield a flawed estimate of water value. Moreover, the aggregation of estimates into a cohesive set of values for a whole region or watershed may result in errors. Care must be taken in the choice of method, and all results, regardless of method used in determination, must be accompanied by explicit documentation of the assumptions required by the analysis.

The United States and particularly its arid and semiarid West is entering a new era with respect to water and water use. As demands for water for nearly all purposes increase and as the true scarcity of the resource is recognized, pressure may mount to shift water to new uses and users. The rules of economic efficiency support these arguments. Making such changes, however, must be viewed in a broader context than that of the primary or first use of the water. Whether the water is used for irrigation, navigation, recreation, or hydropower, that water generates primary, secondary, and tertiary outcomes. Transferring water to a new use may have a profound effect on the supporting resources and on the people left behind as well as those who benefit. Equity and fairness concerns related to such effects on existing users and new users increasingly will be raised.

In the past two decades, States have begun to shift from the traditional water-allocation role to one involving more water-resource planning and management. An active State role will become increasingly necessary for resolving growing conflicts over water use because of the associated social effects of choices made. Federal institutions will also need a strong and committed long-term role in water-resources planning and management to protect national, regional, and individual interests in this vital resource.

CHAPTER V REFERENCES

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VI

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Chapter VI

Technologies Affecting Precipitation and Runoff

Most of the water used by agriculture in the Western United States originates as precipitation, then runoff. The hope exists that large amounts of additional water could be made available by altering these processes a small amount. A variety of technologies have been developed either to increase or predict the surface runoff from watersheds of the Western United States. These include augmentation methods such as weather modification ("cloud seeding"), watershed management through vegetation removal or replacement, and streamflow forecasting. Each of these has been supported by Federal research, and interest in each remains high.

This chapter illustrates the interrelated nature of these technologies and assesses the degree to which they increase or manage precipitation and surface runoff for the region's agriculture. The chapter is based on the extensive research literature about the United States and similar hydrologic environments throughout the world. A definitive regionwide assessment of these technologies cannot be made here. Their effects on distant downstream users may be difficult to measure, their results may not be applicable to large geographic areas, and few data syntheses exist. Considerable disagreement persists, then, regarding the potential of these technologies as well as the legal and institutional ramifications of their application.

Box J

"If we lived in a desert and our lives depended on a water supply that came out of a steel tube, we would inevitably watch that tube and talk about it understandingly. No citizen would need to be lectured about his duty towards its care or spurred to help if it were in danger. Teachers of civics in such a community might develop a sense of public responsibility, not only by describing the remote beginnings of the commonwealth, but also how that tube got built, how long it would last, how vital the intake might be if the rainfall on the forested mountains nearby ever changed in seasonal habit or amount. It would be a most unimaginative person, or a stupid one, who could not see the vital relation between the mountains, the forests, that tube and himself."

SOURCE: Isaiah Bowman, "Headwaters Control and Use—Influence of Vegetation on Land-Water Relationships," *Proc. Upstream Engin. Conf.*, Washington, D.C., pp. 76-95, 1937.

THE WATER SETTING

In the Western United States, a watershed may be as large as that of the Missouri River basin, with a surface area of at least 500,000 square miles (mi²), or as small as an ephemeral tributary to that river, with a surface area of only a few tens of acres. Watersheds in the Western United States, at their largest geographic scale, encompass a wide range of climates, geology, soil and vegetation types, and land use practices. Even the smallest watersheds are seldom homogeneous in all of these factors.

Water may leave a watershed in a variety of ways. The most obvious is surface runoff as a river or stream. Water also may leave a watershed by percolating to ground water. The extent to which this occurs is dependent on the ability of the soil and rocks of the basin to transmit water. Over much of the Western United States, the primary means by which water leaves the watershed is by evapotranspiration (ET). ET is generally greatest in the arid and semiarid portions of watersheds and least in high-altitude mountain watersheds. Thus, ET may account for almost all of the precipitation falling on a watershed in an arid portion of the Lower Colorado River Basin, while it may account for only a small fraction of the precipitation falling in an alpine environment at the headwaters of that river.

Each year, an estimated 1.5 billion acre-ft of water are added by precipitation to the water supplies of the Western United States. Of this amount, approximately 500 million to 550 million acre-ft form the surface runoff of the region, 50 million acre-ft enter into the ground water reserves, and the major portion is returned to the atmosphere by evaporation or transpiration from vegetation. The bulk of the surface runoff is derived from the melting mountain snowpack, which produces an estimated 70 percent, or 350 million acre-ft, of the runoff of the region (table 36).

Table 36.—Variable Percentage of Surface Runoff From the Mountain Snowpack

Estimated snowmelt fraction of the total annual surface runoff for those Western States where melting mountain snowpack is the principal source of surface runoff.

State	Snowmelt fraction of total annual streamflow
Arizona	0.74
California	0.73
Colorado	0.73
Idaho	0.67
Montana	0.70
Nevada	0.65
New Mexico	0.71
Oregon	0.67
Utah	0.74
Washington	0.67
Wyoming	0.74
	0.70

SOURCE: P. Castruccio, H. Loats, D. Lloyd, and P. Newman, *Applications Systems Verification and Transfer Project, Volume VII: Cost/Benefit Analysis for the ASVT on Operational Applications of Satellite Snow-Cover Observations*, National Aeronautics and Space Administration Technical Paper 1828, 1981.

Channeled surface runoff, as occurs in rivers or streams, is of three major types: perennial runoff, which flows throughout the year; intermittent runoff, which occurs each year during certain seasons; and ephemeral runoff, which only occurs following an event such as a heavy rainstorm. While both intermittent and ephemeral runoff contribute at times to the flow of the perennial rivers and streams of the region, they do not constitute a dependable water-supply source, except for specialized local uses. Intermittent and ephemeral runoff characterize much of the valleys and plains of the Western United States, while the perennial rivers almost always have their headwaters in the mountain ranges of the region. The amount of ET will be determined by the amount of available energy required by this process, the seasonal distribution and amount of precipitation, and the nature of density of the vegetal cover.

The ratio between the amount of precipitation falling on a watershed and the amount leaving the watershed as surface runoff determines the "runoff efficiency" of that watershed. As the runoff efficiency increases, greater amounts of precipitation become surface runoff. Runoff efficiency for any given watershed is determined by complex interactions among precipitation, evaporation, and soil-moisture recharge. The demands of evaporation and soil moisture recharge, which must be met before any surface runoff can occur, are relatively constant from year to year, while precipitation may be variable. The interactions among these hydrologic elements are complex and generally small percentage changes in a single element, such as precipitation, will not translate directly into a proportional change in surface runoff. Runoff efficiency in the Western United States varies greatly, from as little as 10 percent in a hot desert environment (where most of the precipitation rapidly evaporates) to as much as 90 percent in a humid maritime climate. Technologies designed to increase surface runoff by changing some element of the hydrologic cycle to increase runoff efficiency must be considered in terms of the wide range of hydrologic regimes which characterized the region.

Any volume of additional runoff produced by modification of a particular watershed will eventually move through the entire river system to the sea or ground water, or be removed by evapotranspiration. The ability to measure any increased volume by the application of technology will diminish as one moves farther from the point of application and as the water is incorporated into the normal, increasing volume of the river system. Thus, the impact of the application of any watershed-management technology that produces additional surface runoff will be most easily measured near the point of application.

Information on impacts of watershed-management technologies that attempt to increase usable runoff or to improve management of that runoff has been derived largely from experimental watersheds. These technologies include: 1) precipitation augmentation by weather modification (cloud seeding), 2) removal or replacement of vegetation to reduce evapotranspiration or to increase snow captured onsite, 3) management of surface water runoff through modification of the surface permeability and landscape to store water or direct it to selected areas, and 4) water-supply forecasting. The impacts of any technology designed to alter the hydrologic cycle within a watershed will be affected by the basin's preexisting water regime, the relationship among the elements of the basin's hydrologic cycle, and the portion of the watershed to which they are applied.

It is useful to consider the major elements of a watershed in order to understand the kinds of specific technologies that might be applicable to increase surface runoff or to improve the ability to manage or forecast the natural or modified runoff. A number of classification systems have been proposed. For timbered watersheds, the U.S. Forest Service has proposed a classification scheme based on the dominant vegetation present (e.g., 14). A similar concept, based on vegetation type, has been used to describe rangeland watersheds where brush or grasses, rather than timber, are dominant (e.g., 11). For development of streamflow runoff forecast models, classification is commonly based on the dominant form of precipitation—i.e., rain or snow--while weather-modification technologies are generally classified in terms of the dominant meteorological process controlling precipitation. Fundamentally, each technology has developed its own approach to the classification of watersheds without reference to the other relevant watershed-management technologies.

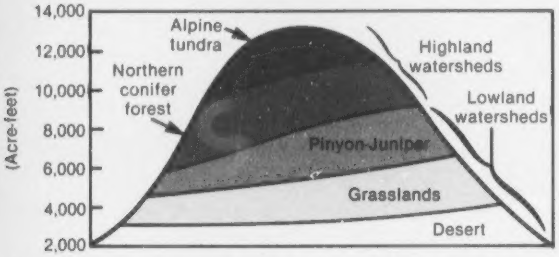
To compare technologies that modify or forecast runoff from watersheds, a simple but useful classification based on altitude above sea level and major topographic features was used in this assessment. In this scheme, watersheds of the Western United States may be viewed as being either "highland" watersheds, those associated with the mountain ranges of the region, or "lowland" watersheds, which are found primarily in the adjacent valleys and plains. While such a system does not completely describe the range of application for any single technology, it enables comparisons between the technologies considered. In addition, it corresponds approximately to the most recent classification scheme proposed by the Forest Service for delineating the ecoregions of the United States (3).

The highland-lowland classification used here is based primarily on major terrain features and vegetation types. In essence, the highland watersheds are located in mountain ranges and have a vegetative cover characterized by alpine tundra at their highest elevations and montane coniferous forests at lower elevations. Lowland watersheds consist of valleys and plains adjacent to these mountains. Some conifers, such as pinyon-juniper stands may be present in the lowlands, but the dominant vegetation is deciduous trees or brush and grasslands (figs. 31 and 32).

Latitude and position on the continent affect the type and density of the vegetative cover in both types of watersheds. The highland watersheds are marine, as in the Pacific Northwest; mediterranean, as in California; or continental, as in the Rocky Mountains. Lowland watersheds are prairie, in the eastern portion of the Western United States; steppe, between the Coastal Ranges and the Rocky Mountains and immediately to the east of the Rocky Mountains; or desert, in the Southwestern United States (fig. 33). In each case, a distinctive

Figure 31.—Vegetation Zones in the Mountains and Plains of Western North America

This diagram shows general conditions that might be expected in the Central Rockies of Utah. To the north, south, east, or west of this region, vegetation may change. For example, to the north and east, the pinyon-juniper zone is absent; in the east, an oak-mountain mahogany zone is present between the grassland and northern conifer forest.



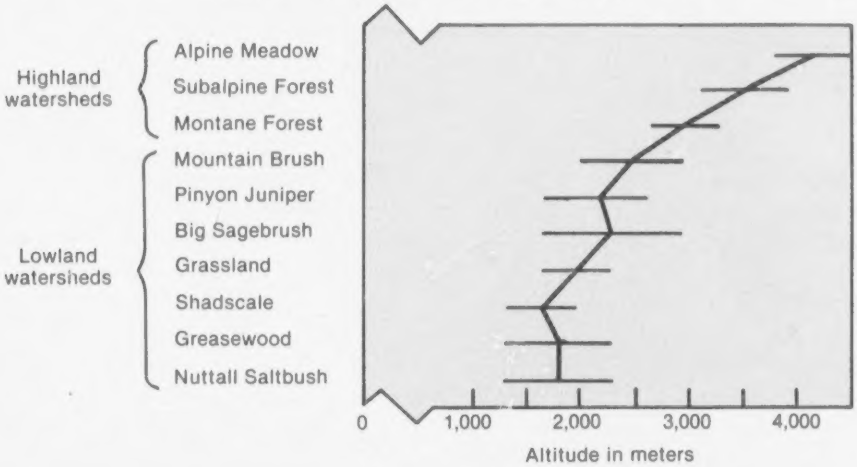
SOURCE: Biological Sciences Curriculum Study, *Biological Sciences: An Ecological Approach*, BSCS Green Version, 4th ed. (Chicago: Rand McNally & Co., 1978).

vegetation type and hydrologic regime have developed in response to precipitation and temperature patterns (3).

A highland-lowland distinction is useful in relating both the form and seasonal hydrologic behavior of water and the varied environments. The highland portion of each watershed is cold and humid relative to the surrounding lowlands. Much of the annual precipitation falls as snow during winter and becomes liquid water for runoff, evapotranspiration, or infiltration into the soil during spring and summer. The lowland portion of each watershed is warmer and drier. Rain is much more common here and snow melts more quickly during the winter or early spring than in the highlands. Snow does not accumulate to the depths common in highland areas. Generally, the amount of precipitation of any form decreases with decreasing altitude.

Highland watersheds generally give rise to perennial streams or rivers. Lowland watersheds are characterized more often by either intermittent or ephemeral runoff. While both forms of runoff are variable to some extent, both seasonally and annually, perennial streams will be less so. In addition, perennial streams and rivers are more likely to be regionally significant in their importance as water-supply sources, while intermittent and ephemeral streams are more likely to have a local, site-specific importance. Technologies to affect surface runoff must be designed with these characteristics in mind.

Figure 32.—Approximate Altitudinal Ranges of Major Vegetation Types in the Upper Colorado River Basin (water resources region 14)

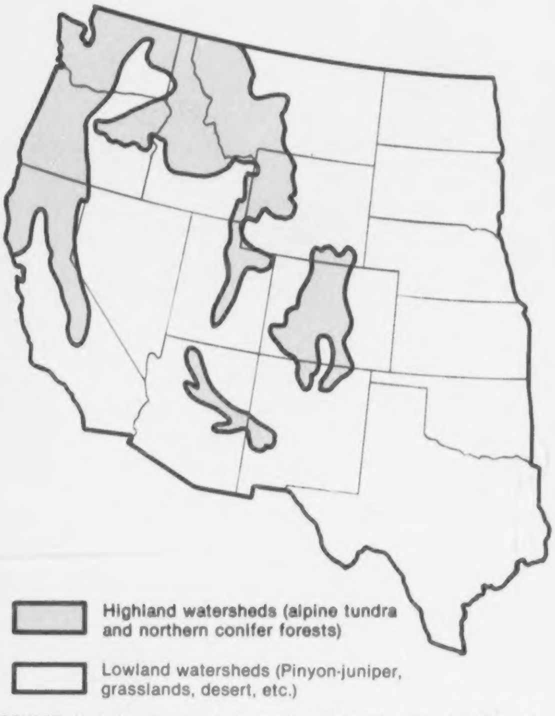


The diagram shows the various ecological communities contained within highland and lowland watersheds.

SOURCE: F. Branson, G. Gifford, K. Renard, and R. Hadley, *Rangeland Hydrology*, Society for Range Management, Range Science Series No. 1 (Dubuque, Iowa: Kendall/Hunt Publishing Co., 1981).

Figure 33.—The Spatial Distribution of Highland and Lowland Watersheds Over the Western United States

Highland watersheds are primarily mountains and consist of northern conifers or alpine tundra biomes. Lowland watersheds are characterized by a variety of grasslands or shrub ecological communities.


Highland watersheds (alpine tundra and northern conifer forests)
Lowland watersheds (Pinyon-juniper, grasslands, desert, etc.)

SOURCE: H. Anderson, M. Hoover, and K. Reinhart, "Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply," *USDA Forest Service General Technical Rpt. PSW-18*, pp. 82-87, 1976

The major biophysical environments that may be present in combination or singly in a watershed are the: 1) alpine tundra, 2) montane forest, and 3) grasslands or shrublands. The alpine tundra is that portion of a mountain range above timberline (the upper limit where tree growth occurs) and is found in most major mountain ranges of the Western United States. The montane forest environment extends from the timberline at the lower edge of the alpine zone to the base of the mountain. Grasslands and shrublands exist on the low-altitude plains and hills extending out from the foot of the mountains. Across these three environments, various land use practices, including timber harvesting, rangeland agriculture, or crop production, may be practiced in some combination. In general, the annual snow/rain ratio and runoff efficiency will decrease from the alpine environment to the grasslands.

The choice of an appropriate watershed-management technology to affect surface runoff is influenced by all these watershed factors. The appropriate technology should be designed for the principal form of precipitation and the percent of surface area in each of the major biophysical environments affected. Transition zones may occur where the snow/rain precipitation ratio or biophysical environments are mixed. In these areas, no single technology may be clearly preferred. Generally, technologies that have been developed to affect surface runoff for onsite or offsite use are specific to a particular set of characteristics in highland or lowland watersheds.

The highland and lowland watersheds, primary water-producing areas of the West, largely are on public lands. As such, Federal agencies responsible for managing these lands will play an important role in affecting the future of water use on arid/semiarid lands, whether through active or passive involvement. Pursuant to their multiple-use responsibilities, these agencies have the mandate to include water resources and water-resources management within their multiple-use objectives. The multiple-use concept already is embodied in a number of Federal laws including the Multiple-Use, Sustained-Yield Act of 1960 (Public Law 86-517) and the Federal Land Policy and Management Act of 1976 (Public Law 94-579). Existing multiple-use statutory guidelines prohibit optimization of a single measurable resource (e.g., timber and cows) at the expense of less quantifiable uses (e.g., watershed and recreation), and they forbid practices that impair continued land productivity (9).

Photo credit: USDA-Soil Conservation Service

Watersheds in the Western United States may be either "highland" areas, consisting of the major mountain ranges of the region, or "lowlands," the surrounding plains and valleys. Highland watersheds consist of montane forests and, above them to the summits of the ranges, the alpine zone. Lowland watersheds are characterized by sparcer forests, shrublands, or grasslands

THE TECHNOLOGIES

Weather Modification

Introduction

Weather-modification technologies, often called "cloud seeding," owe their scientific beginning to one initial experiment that demonstrated that an artificial ice-nucleating agent such as solid carbon dioxide induces the formation of ice crystals in air supersaturated with water vapor with respect to ice (19). The ice crystals grow quickly to precipitable size and fall from the cloud as precipitation that might not have occurred naturally. All modern cloud-seeding technologies have developed from this discovery.

Cloud seeding works in two ways. First, artificial nuclei may stimulate small cloud particles to coalesce. Second, cloud seeding with ice nuclei or solid carbon dioxide (dry ice) may induce freezing and cause the production of large numbers of ice particles, which proceed to grow to precipitable size. In the first case, known as "warm seeding," waterdrops may be introduced into a cloud to start a process that might otherwise take longer. Because modifying a cloud might entail a substantial mass of water in the form of individual drops, finely divided salt or a water-attracting chemical mist is usually used instead. In experiments, for example, a concentrated water solution of ammonium nitrate and urea has been sprayed from an aircraft into a cloud in the form of droplets about 0.20 millimeters (mm) in diameter. Within a minute, the nitrate and urea droplets grew by gathering condensation from the vapor to a 0.50-mm size, a factor of 15 in mass. The 0.50 mm drops were large enough to start a process that may have produced drops 5 mm in diameter only 20 minutes later.

The second method, seeding by dry ice or silver iodide, requires that the clouds being seeded be at temperatures below freezing. If dry ice is used, it has the effect of inducing a massive, rapid cooling that freezes the supercooled water droplets in the cloud. In contrast, silver iodide particles are good nuclei for ice formation because of the close resemblance of their crystal structure to that of ice (21). Whichever seeding material is used, the result is the production of ice crystals that, it is argued, will increase the precipitation efficiency of air masses known to contain significant amounts of supercooled water droplets.

Water-attracting particles and ice nuclei can be introduced into the air mass in different ways. In the first field experiments, dry ice was dispersed from a small airplane (19) and silver iodide was generated at the ground. Ground-based generators are considered to be effective in the absence of a strong temperature inversion, which inhibits convection, and in mountainous terrain, where orographic processes are generally present. Silver iodide is also often released from aircraft with the aim of placing the nucleating agent directly into selected portions of clouds containing liquid droplets.

Cloud-seeding technologies have been tested primarily in two major air mass types: 1) winter orographic air masses, and 2) summer cumulus air masses. Orographic air masses are those that are forced to rise by their passage across mountain ranges and are often associated with major winter frontal systems. Cumulus air masses are those that commonly form during the summer months as warm moist air rises owing to surface solar heating, though they may also occur in post-frontal situations in winter. The seeding of orographic air masses generally is undertaken to increase the amount of snow stored in the highland mountain watersheds during the winter. Seeding cumulus clouds to increase precipitation has the primary objectives of increasing soil water, of inhibiting hail formation in lowland watersheds during the summer, or for direct crop rainfall in areas of small grains, corn, and soybean production.

APPLICATION TO MOUNTAIN CLOUD SYSTEMS

Three decades ago, Bergeron (4) concluded that the main potential for causing considerable artificial precipitation might be found within certain types of air masses as they are forced to rise over mountain ranges. This conclusion was based on the argument that there was more water in the clouds than was being released as precipitation. Considerations assumed a steady and often substantial formation of liquid water for an extended period of time in a fixed location and the probable accumulation of "releasable but unreleased" cloud water at levels with temperatures below 0° C. Generally, the basic criterion for determining whether or not a seeding potential exists is the natural precipitation efficiency of the clouds—orographic or otherwise. The measure of precipitation efficiency is the percentage of the total water in the cloud system that actually reaches the ground. Seeding would not be required where the efficiency is high. On the other hand, seeding may or may not be of value when the natural precipitation efficiency is low.

While precise numerical values are difficult to achieve, a useful basis for evaluating precipitation efficiency is the comparison between water removal by growth of ice crystals and the supply of liquid water in the cloud. To illustrate this idea, the following processes have been compared for a broad range of cloud temperatures: the average rate of formation of liquid water, the average rate of consumption of this cloud water by ice-crystal growth that would occur from natural concentrations of primary ice crystals, and actual average rates of precipitation observed at ground level. Studies show that, with cloud-top temperatures of −20° C or colder, the observed actual precipitation corresponds closely to the rate at which liquid water becomes available in the clouds. In the main, such clouds should have a high natural precipitation efficiency with little corresponding potential for seeding.

When cloud-top temperatures are warmer than −20° C, natural precipitation efficiency should be low. For these cases, observed values of ground precipitation are, in fact, much less than the average amount of condensate available. A potential for seeding can exist in these cases.

APPLICATION TO CUMULUS CLOUDS

In summer in the Western United States, precipitation very often occurs from cumulus clouds. These clouds form as warm moist air rises from the heated earth and are not necessarily associated with large-scale frontal systems. The natural precipitation efficiency of these isolated clouds is quite low. Even the largest clouds—those reaching thunderstorm size—exhibit precipitation efficiencies of only about 10 percent. The important question is whether isolated cumuli constitute promising targets for artificial nucleation by virtue of their comparatively low natural precipitation efficiency. A major difficulty in assessing possible modification potential is the enormous natural fluctuation in all variables.

In determining seeding potential, it has proven useful to subdivide all cumulus clouds into two types: first, those having typically 50 to 100 droplets per cubic centimeter (cm^3) and, second, those with 400 to 1,000 droplets per cm^3. As the total cloud liquid-water contents are not greatly different for the two types, the average droplet radius must be about twice as great in the first as in the second. The clouds with larger droplets have a more rapid coalescence process because fewer collisions will be required to produce a raindrop. In cumuli containing small droplets, the coalescence process would have to operate for a much longer time in order to develop raindrops in sizes large enough to precipitate. On the basis of this, ice nucleants probably offer less potential for stimulating precipitation in cumuli containing large droplets, for such cumuli can, and evidently do, develop rapidly to the precipitation stage naturally. On the other hand, the same picture suggests that cumuli containing many small droplets might be more readily modified artificially by accelerating cloud particulate growth by seeding. This assumes that these cumuli have cloud-top temperatures of less than 0° C and that natural ice-forming nuclei are so deficient that a substantial part of the cloud water is supercooled.

Although this idea seems simple, there have been few experiments that have demonstrated the effect in the field. Early observational programs, such as those in Australia, gave clear-cut results (23), whereas a U.S. study was inconclusive. It is estimated that an operational cumulus cloud-seeding program (e.g., in the high plains) would require a minimum of 10 years, starting from existing knowledge based on a focused and adequately supported effort (25).*

Several States, local government agencies, and private utility companies now are engaged in weather-modification projects in the Western United States. In addition, ongoing and planned large-scale cooperative programs exist under Bureau of Reclamation sponsorship as well as jointly funded cooperative programs with the National Oceanic and Atmospheric Administration (NOAA) (22).

As of 1982, the States in which seeding projects were being conducted were California, Nevada, Utah, North Dakota, and Texas, with planning under way in Colorado, Oklahoma, and Arizona. There are 13 independent project areas in California, 4 in Nevada, 3 in Utah, 3 in North Dakota, 2 in Colorado, and 1 in Texas. Most, if not all, of the programs west of the Continental Divide are conducted in high mountainous areas where snowpack augmentation is the goal. The programs east of the Divide are designed for rain enhancement and/or hail suppression efforts (22).

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*Seeding very large cumulus and cumulonimbus clouds has been undertaken in Kenya, U.S.S.R., Switzerland, France, Canada, and the United States in attempts to decrease damage from hail. Some of these programs claim 30- to 80-percent decreases in hail damage to crops. Others have observed no effects.

SEEDABILITY POTENTIAL

For the Western States, the potential of weather modification for augmenting water supplies is related, in part, to the number of opportunities available for a seeding operation. The fall, winter, and spring months yield between 30 and 50 precipitation events in which opportunities may exist to carry out a modification operation. An event is defined as a storm that is expected to last 6 hours or more and to yield measurable precipitation. Some of these storm events may last up to 3 days. The potential for seeding a storm to produce additional precipitation depends on the existence of supercooled liquid water in the clouds of that storm. The cloud must contain liquid water at temperatures below freezing for the ice phase processes to be effective. If there are only a few "seedable" events available per season at any given location, considerations of economics may become crucial in deciding on the benefits to be accrued from this opportunity-limited situation (22).

"AREA OF EFFECT" PROBLEM

One of the most important issues in weather modification today is the determination of the "area of effect" of operational and/or research cloud-seeding programs. In its fullest sense, area of effect encompasses not only the microphysical and dynamic aspects of cloud-seeding effects but questions of water budgets, optimization of seeding technology, and State and international boundary issues.

In particular, it is important for the research community to determine the impact (if any) of seeding programs in one State on the water supplies of an adjacent State or area. It is well known that in a number of weather-modification projects, there have been indications of noticeable effects outside the "intended target areas," sometimes at surprisingly large distances, especially in the downwind direction. The programs in Switzerland, Israel, and Colorado, in particular, have been cited as examples (22).

RIGHTS TO USE OF AUGMENTED WATER

Perhaps no other aspect of weather modification is as perplexing as the concept of ownership or use rights regarding the water generated by cloud-seeding projects. No body of law exists to deal with such problems; laws were created to deal with surface waters and were later expanded to cover ground water. Stretching these earth-bound laws to cover atmospheric moisture that does not confine itself to a watershed, let alone to political boundaries, is a difficult process (10).

The principal questions for weather modifiers relate to the share of "new" water that might go to each modifier and the verification of water-use rights based on weather-modification activity. The questions become increasingly complex as possible variables are considered—Does a senior rightholder downstream have any rights to the "new" water in dry years? Is a Federal water right created for water that the U.S. Government generates through its cloud-seeding efforts? Answers to questions such as these will depend on how the new water is classified. Classification hinges conceptually on identifying the water as "developed" water—i.e., water not previously a part of the natural yield of a river basin but rather additional water made available from the weather modification activities.

It is essential that the weather modifier be able to prove that additional runoff has actually been developed before securing a right to its use. It is likely that the procedure would require the modifier to demonstrate that a specific quantity of water in the stream would not have been there under normal conditions—i.e., without cloud seeding.

The problem is narrowed to that of "proving" a quantifiable increase over the natural streamflow. Eventually, the technology may be developed to enable definitive and accurate measurement of such increases, but it is not possible now, as discussed earlier, and a great deal more knowledge must be available before anyone can define how much water is developed from cloud seeding. Until the science of weather modification offers some concrete proof of its effectiveness and measures this effectiveness, any precipitation so produced almost certainly will be considered part of the natural yield and will be distributed in accordance with established rights.

Assessment

Compared to other augmentation technologies such as evaporation control or interbasin transfer, the technology of weather modification can be viewed as an economically attractive method for bringing additional water into water-short regions of the Western United States. However, the viability of the technology rests on the occurrence of suitable atmospheric conditions in these regions. Drought years are the result of low rainfall, an indication of a low frequency of precipitating cloud systems. Weather-modification technology depends on the availability of suitable cloud conditions for its application. Consequently, the high, mountainous regions of the Western United States probably offer the greatest and most reliable potential for precipitation augmentation because these regions receive the winter snows and thus provide the springtime runoff water supplies to agricultural lands and to ground water. These highland regions are cooler for longer periods of time than lowlands and thus provide a longer season for accumulation of snow and storage of water as snow.

In general, the major difficulty faced in weather-modification technologies is the inability to detect statistically significant changes in either snowpack water-equivalent depths, snowmelt runoff, decreased hailstone size, or increased rainfall at the ground surface. While fairly substantial increases in the volume of water stored in the winter snowpack have been claimed, these claims have been challenged by other researchers. In at least one case ("Project Skywater," San Juan Mountains, southwestern Colorado), after a number of years of experimental seeding operations, the Bureau of Reclamation concluded that a slight, but statistically insignificant, *decrease* in streamflow had occurred.

These discrepancies may be due, in part, to an incomplete understanding of snow-crystal or hailstone growth and the precipitation processes involved. Also a contributing factor is the incomplete understanding of the processes affecting snowpack accumulation, melt, and runoff in the mountain environment. There are problems in selecting suitable air masses and in understanding both the physical processes that control the natural production of ice nuclei and the efficiency of the nucleation process. Similarly, the way in which seeding materials are dispersed in air masses, the origin and location of supercooled water in air masses, and the effects of small changes in the purity of seeding agents need further study. The definition of useful verification standards is another major area needing attention.

The most valid line of research, in light of these problems, may involve studies of air mass characteristics to understand better the nature and behavior of an air mass prior to and during a seeding experiment. Attempts are now underway to develop more objective verification procedures based on properties of the deposited snow rather than on statistical relationships between precipitation and runoff. More sophisticated studies of the mountain snow accumulation and runoff regimes must be an integral part of future cloud-seeding experiments.

The environmental effects of increased precipitation as a result of cloud seeding have been examined on a number of occasions. Short-term environmental effects are discussed in the Colorado River Basin Pilot Project Final Environmental Statement, The Project Skywater Programmatic Final Environmental Statement, and the Sierra Cooperative Pilot Project Environmental Assessment (22). These studies conclude that the incremental increases in precipitation over the short term involved with cloud-seeding research programs do not have significant adverse impacts on environmental-ecological systems. Incremental increases are usually within the historic natural variability of seasonal and annual precipitation in the study areas (22). As additional information and experience have become available, scientific concerns about potential long-term negative environmental impacts caused by precipitation augmentation have eased (22).

Surface Watershed Management

While precipitation augmentation through cloud seeding may be considered a watershed-management technology, current use of this term restricts it to those practices designed to modify the volume or timing of surface runoff by surface modifications, such as vegetation manipulation. This section discusses technologies that attempt to increase surface runoff for offsite use or to retain precipitation onsite to promote plant growth and stabilize the soil. The technologies will be discussed in the context of the watersheds they affect.

In general, technologies that have been developed to affect surface runoff by surface modification are site-specific in both highland and lowland watersheds. Transitional zones also exist where the hydrologic environment is a mixture of montane forests and alpine tundra (at the upper limit) or grasslands and brushlands (at the lower). In addition a mixture of precipitation can occur in each watershed type, depending on elevation. In transition zones, technologies from either highland or lowland watersheds may be applicable, and careful evaluation is necessary for selecting the appropriate technology for a particular transition zone.

Highland Watersheds

Typically, highland watersheds are composed of two biophysical environments or zones: the untimbered alpine belt above timberline and, below this, the montane forests. These two zones are commonly separated by a transitional zone which most workers refer to as the "subalpine." Surface runoff, ground water recharge (where it occurs), and the liquid water necessary for plant growth is supplied largely by the melting of the snowpack that forms during the winter.

Highland watersheds play a vital role in supplying water to rivers in the Western States. The percentage of total surface runoff passing annually through a river or stream which originates from the melting of the snowpack of highland watersheds varies widely; however, for the 11 westernmost States, researchers estimate that between 70 to 75 percent of the total annual surface runoff of the region originates from this source (e.g., 7).

In addition to their importance as water-yielding areas, highland watersheds have many other uses. Domestic and wild animals graze in the grasslands of the alpine belt and in meadows within the montane belt. In the montane forests, commercial timber production is the most important. Other potential or actual uses include recreation, wildlife habitat and, locally, mineral extraction.

THE ALPINE ZONE

Introduction.—The alpine zone is a relatively cold, wet environment, where precipitation falls as snow during every month of the year and snow deposits persist throughout the year. Precipitation amounts, which commonly increase with elevation, are highest in the alpine zone. Coupled with the low amounts of evapotranspiration and infiltration, the alpine regions produce the highest runoff efficiency (the ratio between precipitation inputs and streamflow) in the West.

The snowcover of the alpine zone is unevenly distributed, a result of high winds that often accompany the storms moving across the region and the rugged topography, which traps blowing snow. Large areas blown completely free of snow alternate with deep snowdrifts that form in sheltered sites. The concentration of snow into these snowdrifts causes snowmelt to be delayed relative to areas where snow deposits are more uniform. This, in turn, delays runoff until later in the season than is the case with the snow cover at lower altitudes. It is this storage and delay of snowmelt runoff until the warmer summer months, when demand in the lowlands is at a maximum, which contribute to the hydrologic importance of the alpine belt.

The alpine zone is not uniformly distributed throughout the mountain ranges of the Western United States. Estimates of its total surface area are difficult to make. One estimate places the total alpine acreage in the West at approximately 10 million acres (20), or slightly less than 10 percent of the acreage of montane forests in the region. A more recent estimate suggests that the actual area may be closer to 8 million acres.

Hydrologic studies in the alpine region of the Western United States have been scattered and sporadic. Studies specifically dealing with aspects of the hydrologic cycle as they influence snow accumulation, melt, and runoff in the alpine belt have been undertaken by only a few investigators, and only broad generalizations are possible from these studies.

Existing research indicates that the alpine region is naturally efficient in producing runoff and constitutes an important water source for the region. For example, in Colorado, estimates indicate that the alpine belt, which comprises about 3.5 percent of the surface area of the State, produces approximately 20 percent of the State's surface runoff (20). In Utah, it is estimated that 10 percent of the State's highest elevation areas yield 60 percent of its runoff; this area and the next lower 15 percent of the surface area, account for 90 percent of the total runoff of the State (20).

Relatively few technologies have been proposed for manipulating runoff and water yield in the alpine belt. In part, this is because of the difficulties of access to and movement in an environment that generally is cold, windy, and snow-covered during much of the year. Additionally, research in this environment has had little funding support from the public and private sector, owing to the apparent lack of management opportunities. Studies to date have focused primarily on the installation of snow fences to trap blowing snow, to increase local snow storage, and to reduce water losses from sublimation during wind transport (16). Other studies have looked at the possibilities of rehabilitating parts of alpine watersheds that are disturbed by other activities, such as mining (13).

Assessment.—A major limitation for application of snow-fencing technologies in the alpine zone is the scarcity of favorable sites for installation of fences. Suitable sites constitute a small fraction of the total alpine area (6).

Research indicates that some potential exists for rehabilitating many presently disturbed alpine sites, but only more intensive management practices can help reduce the impacts of future disturbances (13). Severely affected sites, such as abandoned or active mine dumps, generally require intensive revegetation and rehabilitation efforts. The success of these efforts requires an extensive commitment of manpower, money, and expanded basic and applied research programs.

Two major considerations affect any management activities in the alpine. First, because of the apparent high natural runoff efficiency, the alpine may be most productive in yielding water through passive management rather than through the application of manipulative technologies. Second, a conservative approach to the development of nonwater resources may be the most prudent course until a better understanding of the hydrologic significance of this environment is obtained. Future environmental problems may become more severe as the result of other human activities on the alpine zone—e.g., mining, grazing, and recreational uses (table 37). Eventually, these kinds of activities may in turn affect the quality and quantity of runoff produced in that zone (13).

THE MONTANE ZONE

Introduction.—The montane zone generally extends downward from the timberline to the foot of the mountain ranges. Its vegetation is largely coniferous forest, but the types of trees and their spacing vary in a complex fashion with latitude and altitude. The dominant precipitation form is winter snow. The headwaters of eight of the nine major water re-

Table 37.—Summary of the Nature and Extent of Alpine Disturbances in the Western United States as of 1976

	Extent of disturbance		
Nature of disturbance	Hectares	Acres	Percent of total disturbed
Grazing	256,194	633,056	74.5
Recreation	38,140	94,244	11.1
Mining	34,677	85,686	10.1
Roads	12,748	31,499	3.7
Pipelines	683	1,689	0.2
Power lines	289	714	0.1
Reservoirs	274	676	0.1
Other	795	1,964	0.2
Total disturbance	343,800	849,528	100.0
Total area of alpine	2,915,951	7,205,315	—
Percent disturbed	11.8	11.8	—
Additional anticipated by 1980	57,646	142,444	16.7[a]

[a] Based on the 1976 total.

SOURCE: R. Johnston, and R. Brown, "Hydrologic Aspects Related to the Management of Alpine Areas," USDA reprint from: *Special Management Needs of Alpine Ecosystems*, Intermountain Forest and Range Experiment Station, Ogden, Utah, 1979.

source regions of the Western United States lie in this zone (see ch. III).

About 120 million acres of the Rocky Mountains lie within the montane zone. Snow water-equivalent accumulation depths in this area at the end of the winter average about 2.5 ft annually, or approximately 320 million acre-ft of water (6). In the Cascade/Sierra Ranges, the other major mountain chain of the Western United States, approximately 30 million acres lie within the montane zone (2).

Experimental research dealing with the relationship between forests and surface streamflow has been conducted for at least 100 years (17). The first recorded U.S. experimental study of the effects of forest removal as a planned land-use change on streamflow started in 1910 at Wagon Wheel Gap, Colo. By the 1960's, work accelerated on the potential for water production through timber-removal techniques in the montane zone (2,14). Some 200 forested experimental watersheds were under study throughout the United States by 1960. In the Western United States, at least six experimental watershed areas have been instrumented and studied for water production. These experimental watersheds located in Arizona, California, Colorado, and Oregon, represent a variety of hydrologic environments (2).

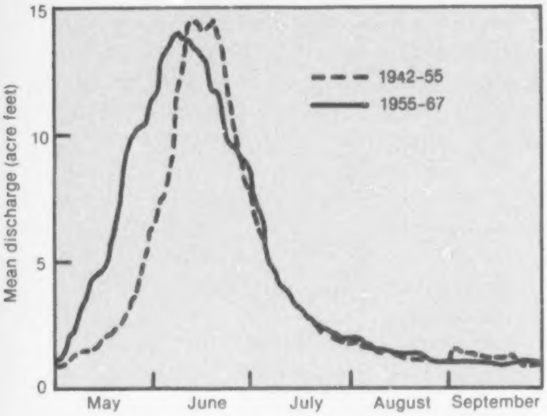
Almost all experimental work on water-production technologies in these watersheds has been conducted by the U.S. Forest Service, the Federal agency responsible for management of most montane areas in the Western United States. Most work has involved timber removal, either through clearcutting, patch-cutting, or thinning. Clearcutting is a procedure that totally removes forest cover and may involve an entire watershed. This procedure is designed to minimize transpiration losses. Patch-cutting involves opening the forest cover in a patch or strip whose width is about three to eight times the tree height and whose area totals 30 to 50 percent of the forest area. Patch-cutting is designed to redistribute winter snowfall by concentrating it within openings for maximum capture and storage.

Assessment.—In certain situations, vegetation management through timber harvesting may produce local increases in water yield. Application of this technology to increase surface runoff has generally been restricted to experimental watersheds. Work remains to be done on its general application and value on a larger scale and to unstudied watersheds of the Western United States for purposes of supporting arid/semiarid agriculture. Also needing more attention are the extent and nature of the impacts of this technology on other major elements of the hydrologic cycle.

A number of attempts have been made by the Forest Service to estimate and predict the site-specific, water-related results of its timber removal experiments. Early evaluations of results were based on classical hydrologic methods involving paired-basin comparisons and before/after treatment studies (6). The comparisons have since been augmented by basin simulation models.

Studies of the Fool Creek basin at Fraser, Colo., have been the basis for Forest Service predictions that streamflow water yields from Rocky Mountain forests might be increased by 2 to 3 inches annually through selective patch-cutting (fig. 34) (14). In this central Colorado

Figure 34.—Average Runoff Hydrographic for Experimental Watershed



Average runoff hydrographs for a 14-year period for the Fool Creek experimental watershed in Colorado. The solid line is the runoff for the 13-year period following timber removal. Note that the primary effect was an earlier onset of spring runoff.

SOURCE: Charles F. Leaf, *Watershed Management in the Central and Southern Rocky Mountains: A Summary of the Status of Our Knowledge by Vegetation Types*, USDA Forest Service Research Paper RM-142, March 1975.

watershed, 40 percent of the old-growth lodgepole pine and spruce-fir forest were strip-cut in 1955. Results from experimental forest modification in the west coast montane forests have led to similar predictions (2).

Questions of whether these increases can be maintained and whether they can be detected at downstream arid/semiarid agricultural sites are important, both in terms of the technology potential and its economic feasibility for Western agriculture. The maintenance of runoff increases depends on several variables such as the amount of snow stored in drifts, the amount of sustained reduction in evaporation, natural regeneration features of the harvested area, and measures applied to control regrowth (2). For example, new plant growth may reduce surface water yield (2,20). If this hydrologic response occurs, regrowth must be controlled to sustain initial water-yield increases. Moreover, using existing stream-gaging technology, it may be difficult to detect increased yields at points downstream where arid/semiarid agriculture is practiced because such increases are relatively small when combined with the entire volume of watershed runoff at the point of use.

Application of runoff results obtained in experimental watersheds to unstudied watersheds presents other questions in view of the range of hydrologic responses possible from site to site (box K). Within unstudied watershed areas, various elements of the hydrologic cycle still are unmeasured. Inferences must be drawn and assumptions made concerning the manner in which these unmeasured variables interact. Researchers often use statistical trends of hydrologic relationships identified in studied watersheds to predict hydrologic effects from timber removal in other watersheds. These methods must be used with care because the extension of results from experimental watersheds to other areas sometimes may not be valid (17).

The meaning of experimental results regarding the relationship of timber removal and increased surface runoff remains unclear. Studies of the natural hydrologic activity of a subalpine forest in the Appalachian Mountains in the Eastern United States found that 42 percent of the total annual precipitation to that watershed was added by cloud-droplet condensation on the trees of the watershed. According to this research, if this forest vegetation were removed, total precipitation reaching the surface from that part of the watershed would be reduced and runoff would decrease. Some Russian watershed-management studies have produced results indicating that in forests where almost all annual precipitation occurs as snow, and runoff is produced primarily by the spring snowmelt, streamflow decreased as the forests were removed (17). More recent studies reported by the Forest Service tend to support the Russian results. Leaf (14) found that "[w]hen 40 to 50 percent of the mature spruce-fir timber volume is removed from north slopes on a selection-cut basis, water yields may actually decrease somewhat."

More recently, Hawley and McCuen (12) analyzed the relationships that exist between water yield and 17 environmental variables for 605 watersheds in the Western United States. They found that the 11 westernmost States could be best represented by five hydrologic regions (fig. 35). In each of these regions, precipitation was the most important factor in determining water

Box K.—Managing Vegetation for Water Production: Perspectives From the U.S. Forest Service

A review of recent U.S. Forest Service literature that considered the possibility of using forest-management practices to increase water yields illustrates some of the complexities associated with application of this technology. According to their research (Hibbert, 1983; Kattelman, et al., 1983; Troendle, 1983; Harr, 1983; and Douglass, 1983), each of the major forest and range biomes of the United States shows potential for water-yield augmentation from forest management. For example, in the Eastern United States, scientists report that "we know how to manage forests to improve water yield and the potential for increasing the water supply is enormous" (Douglass, 1983). Similarly, in the mountainous regions of western Washington and Oregon, the potential for augmenting water yields appears high (Harr, 1983). Some potential also exists for increasing water yields by managing rangeland vegetation on watersheds where average precipitation exceeds 18 inches per year, in some regions of the Colorado Rockies, and in parts of California (Hibbert, 1983; Troendle, 1983; and Kettlemann, et al., 1983).

Notwithstanding these results, these same researchers caution that the expectation that vegetation manipulation can and will provide significant additions of water for Western agriculture may not be realized. Kattleman and associates report that the large streamflow increases demonstrated on small experimental watersheds in California's Sierra Nevada diminish rapidly when spread over a major river basin under multiple-use management. Furthermore, these researchers note that the absence of large-scale studies limits their conclusions to little more than conjecture.

This is not an isolated problem. In the Rocky Mountains, Troendle reports that the role of snowpack manipulation and evapotranspiration modification is not well defined. Moreover, Troendle adds that a watershed's capacity to store water and yield "excess" water varies across the area, and from a practical standpoint, only a small part of the watershed is now available for vegetation management. Others have concurred with this opinion. On lowland rangelands, Hibbert estimates that less than 1 percent of the Western rangelands can be managed to increase water yield and that little or no increase can be realized by eradication of low-density brush and certain woodland types. Scientists in the Pacific Northwest concluded that, realistically, watersheds will not be managed to produce more water (Harr, 1983).

SOURCES: James E. Douglass, "Potential for Water Yield Augmentation From Forest Managment in the Eastern United States," 1983. R. Dennis Harr, "Potential for Augmenting Water Yield Through Forest Practices in Western Washington and Western Oregon," 1983. Alden R. Hibbert, "Water Yield Improvement Potential by Vegetation Management on Western Rangelands," 1983. Richard C. Kettlemann, Neil H. Berg, and John Rector, "The Potential for Increasing Streamflow From Sierra Nevada Watersheds," 1983. C. A. Troendle, "The Potential for Water Yield Augmentation From Forest Management in the Rocky Mountain Region," 1983. All of the above are in *Water Resources Bulletin 19*, in press.

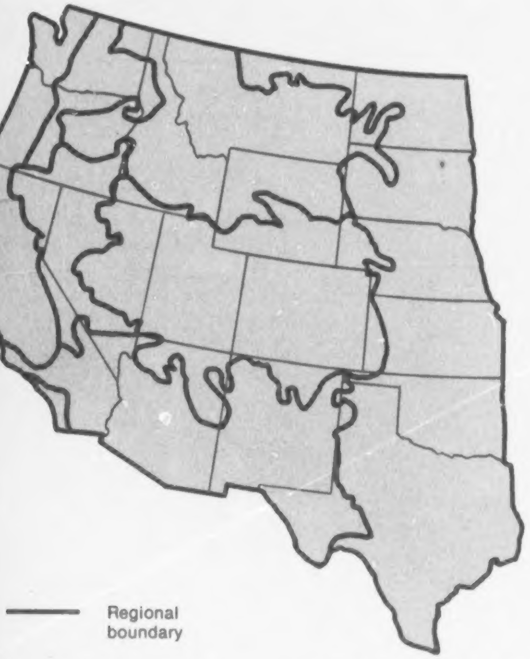
yields, followed by elevation and air temperature. Land-use variables, including vegetation cover density, did not correlate well with water yield. For purposes of predicting water yield from a Western watershed, vegetation cover density "did not significantly improve the accuracy of the estimates where the precipitation, elevation, and temperature variables were also used in the estimation equation."

Such studies as these underscore the need for additional research before timber removal from the Western montane is a generally acceptable technology to increase water supplies for downstream arid/semiarid agriculture. At some sites it may be difficult to determine with any certainty the short-term effects of timber removal on the hydrologic activity of the various components affecting the arid/semiarid agricultural area. It may become even more difficult to determine with some degree of accuracy the long-term hydrologic effects and potentials of different watersheds for Western agriculture and development in general.

It has been suggested that the effects of timber harvest activities on soil erosion and increased sedimentation may far outweigh any beneficial effects on streamflow (8). The amount of soil erosion and sediment production that may result from timber removal will be related to local variation in climate, terrain,

Figure 35.—Regions of Hydrologic Similarity

Regions of hydrologic similarity, based on the relationship between annual runoff and precipitation, elevation, and temperature variables in the Western United States. No two regions respond in the same way to these controls on runoff.



SOURCE: M. Hawley and R. MuCuen "Water Yield Estimation in Western United States," *J. Irrig. and Drainage Division, Proc. A., Soc. Civ. Eng.*, 108 (No. IRI):25-34, 1981.

vegetation, and the type and size of timber harvest undertaken (fig. 36). Forest Service literature indicates that most forests in the Western United States have a natural sediment yield of approximately 45 tons/mi²/yr; logging operations have increased this annual yield to between 200 and 2,000 tons/mi², depending on the particular logging technology employed (2).

Cumulative environmental impacts of any regrowth control measures must also be assessed. If regrowth control involves repeated use of mechanical or chemical measures, additional environmental impacts may be created both onsite and downstream through increased chemical pollution and sedimentation.

Finally, the potential of timber-removal technologies in the montane for increasing surface runoff involves the question of scale. Opportunities for application of timber-removal technology for water production exist on a relatively small portion of the total forested acreage. A realistic expectation of the amount of additional water that could be produced in the next 50 years under a timber-removal approach to watershed management in the montane forests would be approximately 3.7 million acre-ft (2). A large but unspecified amount of this water would be produced by Western forests. This figure represents less than 1 percent of the present mean annual runoff from the 17 Western States and, as has been noted previously, would be difficult to detect by existing stream-gaging networks at distances from the modified watershed where arid/semiarid agriculture is practiced. Some question exists also regarding the desirability of extensive modification of Western surface area, especially when wilderness and other less modified, natural mountain environments are involved. A watershed-management technology that might substantially alter a minimum of 10 percent of the Western forests and may not produce a significant addition to the water needs of arid/semiarid agriculture may be difficult to justify from the point of view of agriculture.

Lowland Watersheds

INTRODUCTION

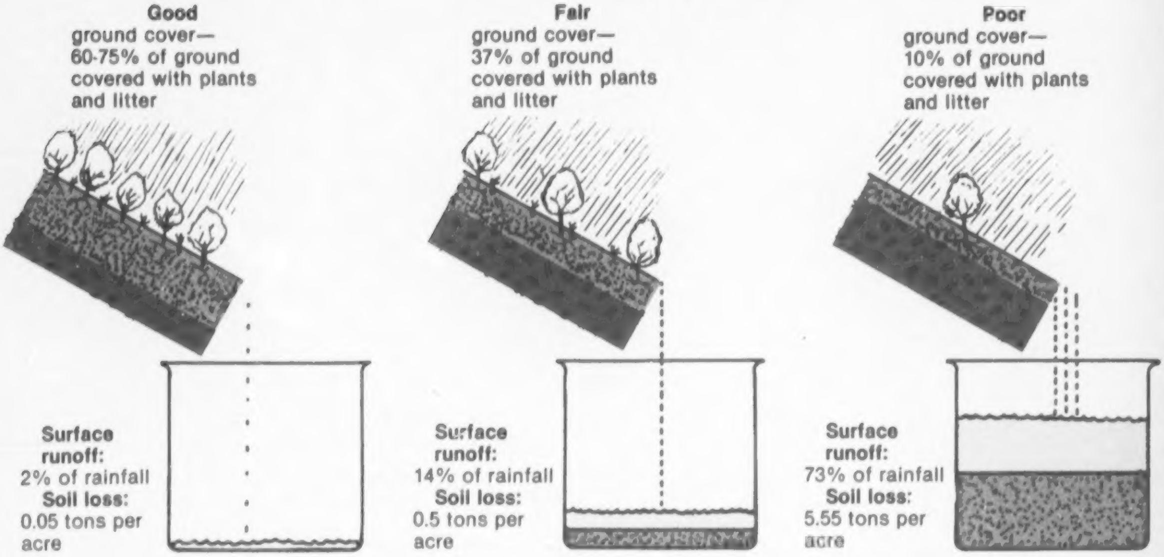
Many lowland watersheds are used for livestock grazing and the technologies affecting surface runoff are often associated with range management. The technologies applied to lowland watersheds that are considered in this section are designed to produce additional surface runoff for offsite use. Broadly, the technologies consist of: 1) vegetation removal and replacement (brush control), and 2) runoff agriculture. Both types of technologies are used to increase water yields by facilitating a shift of water from one component of the hydrologic cycle to another.

VEGETATION REMOVAL AND REPLACEMENT (BRUSH CONTROL)

Introduction.—Much of the vegetation in lowland areas consists of grasses, forbs, and shrubs. Technologies that manipulate vegeta-

Figure 36.—The Effect of Watershed Condition on Rainstorm Runoff and Erosion

2.44 inches of rain in 1 hour


Good
ground cover—
60-75% of ground
covered with plants
and litter
Fair
ground cover—
37% of ground
covered with plants
and litter
Poor
ground cover—
10% of ground
covered with plants
and litter
Surface runoff:
2% of rainfall
Soil loss:
0.05 tons per acre
Surface runoff:
14% of rainfall
Soil loss:
0.5 tons per acre
Surface runoff:
73% of rainfall
Soil loss:
5.55 tons per acre

The effect of watershed condition on rainstorm runoff and erosion (average of 3 plots for each condition) on a subalpine watershed in the Great Basin experimental watershed, Utah.

SOURCE: A. Croft and R. Bailey, *Mountain Water*, Intermountain Region, U.S. Forest Service, Logan, Utah, 1964.

tion on these sites can have two purposes: 1) to increase offsite water yield by replacing deep-rooted shrubs with shallow-rooted grasses or forbs that consume less water (also see discussion of phreatophyte management in ch. VII), or 2) to increase soil water available to forage plants by controlling less palatable shrubs (see chs. IX and XI).

Vegetation removal can be accomplished in several ways, and each method has different effects on vegetation and soils. For example, mechanical brush control is used widely in some areas. Some types of mechanical brush control (e.g., hand slashing, shredding, roller chopping) remove only the top growth of the plant and result in minimal soil disturbance; others (chaining, cabling, disk plowing, grubbing, railing, bulldozing, and root plowing) remove the entire plant and can result in extensive soil disturbance. Generally, high labor and energy costs are associated with these practices, and rough terrain can limit their application.

Herbicide application can also be used to control vegetation on some shrub-dominated rangelands. Generally, herbicides have an advantage over some other brush control methods because of their relatively low costs, selectivity in control, reduced labor requirements, safety and utility in rugged terrain, maintenance of ground cover, and minimal soil disturbance (5).

A third method of brush control is by fire, the oldest known practice to manipulate vegetation. Prescribed burning is an inexpensive and often effective type of control that can be used in combination with other brush control methods for long-term brush control. However, in some cases, brush areas cannot support a fire, and because the burned land is denuded for a short period of time, the potential for erosion may be high, especially on steep land or where the soil is not firm.

Finally, vegetation can be manipulated through biological conversion or elimination.

These methods employ grazing animals, insects, or pathogens to control plants. The control agent can either change plant composition directly or indirectly by reducing the vigor or reproductive ability of the target plant or by promoting disease.

Assessment.—The effects of brush control on the hydrologic characteristics of a watershed are a result of the interactions among the vegetation, the type of control used to manipulate vegetation, site characteristics (e.g., soil and slope), climatic factors (e.g., rainfall amounts and distribution and storm intensities), weather before and after application, and posttreatment practices (5). Because of the normal variability of these factors, the effects of brush control will vary naturally over time and from area to area.

To date, the evaluation of brush control on the hydrologic characteristics of watersheds has received little research attention (5). Instead, most studies have focused on livestock response or vegetation change as a result of vegetation manipulation.

Some research suggests, however, that brush control may increase offsite water yields under certain site conditions. For example, in heavy brush-infested chaparral or mesquite watersheds that receive at least 20 inches (508 mm) of precipitation each year, vegetation manipulation may increase water yields from these sites, but brush control must be maintained (5). Limited offsite water-yield increases can also be expected by converting brush to grass and forbs at the higher precipitation zones of pinyon-juniper or mountain big sagebrush watersheds. On other rangeland watersheds, however, when shrubs are replaced by grasses and forbs, the herbaceous vegetation uses the available soil moisture equally well, and little or no offsite water-yield increases can be expected.

Brush control to increase offsite water yields has been restricted to relatively small experimental sites. Many questions remain about the application of this technology on a larger scale and under different conditions (e.g., vegetation types, soil types, topography, and brush control practices). Environmental effects of these practices also require resolution. In some cases, large-scale vegetation removal could result in accelerated soil erosion and sediment production, degraded water quality, increased flood hazard, and diminished fish and wildlife habitat. Application and maintenance costs must be determined and compared to the benefits derived from their use.

The following plant communities are considered to be especially troublesome to range managers, though they are not the only plants considered problems. Rather, these examples represent some of the range plant communities where hydrologic data are available:

Sagebrush-Dominated Rangelands.—Sagebrush-dominated rangelands are most abundant in the intermountain region, and some range managers estimate that these areas produce forage at about one-half of their potential (5). Sagebrush (*Artemisia*) is a natural component in many plant communities but readily replaces the grasses under heavy grazing pressures. Since the 1940's, a major effort has been made to clear sagebrush-dominated lands and reseed these areas to introduced grasses, such as crested wheatgrass (*Agropyron cristatum*).

Most research on sagebrush-dominated rangeland has evaluated livestock response or vegetation change as a function of brush control (5). In studies of the influence of sagebrush control on hydrologic variables, research indicates that infiltration rates, sediment production, runoff, and erosion will vary with location and type of brush control. For example, herbicide application usually has the least effect on hydrologic characteristics (5). Mechanical methods of brush control have a limited effect on offsite water yields and sediment production, depending on the degree of soil disturbance, the success of reseeding operations, and other site characteristics (5). The effect of prescribed burning on hydrologic characteristics has not been studied on sagebrush dominated rangelands. In general, research shows that sagebrush or grass vegetation use most of the available soil water, and brush control will not increase offsite water yields, although a large increase in forage production can be expected.

Pinyon-Juniper Dominated Rangelands.—Pinyon (*Pinus*)-juniper (*Juniperus*) woodlands cover extensive areas of some watersheds in Arizona, Colorado, New Mexico, Nevada, Texas, and Utah. They occur mostly at intermediate elevations in areas receiving less than 20 inches (500 mm) of precipitation each year and usually have limited commercial value. These trees intercept precipitation, which is then evaporated without reaching the ground, or consume water through transpiration that might otherwise be available for forage plants. Pinyon-juniper woodlands typically have low livestock-carrying capacities, a result, in part, of tree-stand density and of the invasion of trees into grassland.

Mechanical methods of brush control, such as slashing, bulldozing, and chaining, are the primary methods used to control this vegetation, although fire and herbicide application have also been employed. Studies that have evaluated the influence of pinyon-juniper control on watershed variables have focused mostly on offsite water-yield increases after application. Results of these treatments have varied. For example, one study of the Beaver Creek watershed in Arizona applied three different brush-control techniques (cabling, herbicide application, and hand slashing) to paired watersheds in an effort to boost water yields (5). Herbicide application significantly increased runoff, but hand slashing and chaining had little effect on runoff, possibly the result of surface modifications that trapped runoff. Based on limited sediment data, no significant change was observed in sediment yield after cabling operations or herbicide applications. Other measures of water quality (e.g., total dissolved solids, calcium, magnesium, sodium, potassium, and chloride) were lowest in herbicide-treated watersheds and highest from the cabled watershed (5).

Photo credit: USDA-Soil Conservation Service

Junipers being cleared with an anchor chain pulled by two tractors as a demonstration to develop methods to reduce clearing costs on good range sites

In another study, Wright and associates (5) studied prescribed burning of bulldozed ashe juniper (*Juniperus ashei*) on six paired microwatersheds (0.02 to 0.19 ha) in west-central Texas and found significantly increased runoff and soil erosion on moderate and steep slopes. Controlling pinyon-juniper on gentle slopes (1 to 4 percent) had minor effects on water yields and soil erosion. Sediment loss continued on the moderate and steep slopes until vegetation and mulch cover reached about 70 percent, a period of about 9 to 15 months on moderately steep watershed and 15 to 18 months for the steep watershed.

Chaparral-Dominated Rangelands.—Chaparral refers to dense stands of shrubby plants dominated by broadleaf and narrowleaf, nondeciduous species, many of which vigorously sprout following removal of the aboveground parts. Chaparral is common to the Southwest and California and is characterized by shrubs such as live oaks (*Quercus*), mountain mahogany (*Cercocarpus*), manzanita (*Arctoscaphylos*), and ceanothus (*Ceanothus*). Watershed research in chaparral areas has been concerned with offsite water-yield increases from converting chaparral-dominated watersheds to perennial grasses or the effect of fire on erosion.

Mechanical, herbicide application, and prescribed burning have been used to control chaparral. However, many chaparral species are well adapted to fire, and this method alone is not an effective control. Mechanical control methods are often limited by terrain and are most suited to nearly level areas.

Brush control on chaparral areas that receive less than 20 inches (500 mm) of precipitation annually will result in minor or no water-yield increases (5). Where precipitation is greater, the potential for increased yields appears to be good; however, large variations in treatment response are not well understood.

Use of fire as a brush-control method in chaparral areas reduces soil protective cover, produces a water-repellent layer in the soil, and causes increased surface runoff and soil movement with relatively small storms (5). The results can increase the danger of floods, increase erosion and sediment yields, and facilitate soil slippage and landslides (5). Elevated levels of nutrients in streamflow following fire may also be associated with the high levels of erosion.

Mesquite-Dominated Rangelands.—Mesquite (*Prosopis*) is an aggressive competitor and often forms dense tangles of brush that reduce range forage production and accessibility to grazing animals. Many species and varieties of mesquite are recognized—e.g., honey mesquite and running mesquite.

Research on the hydrologic effects of brush control on mesquite is very limited. Where studies have been conducted, control of honey mesquite by several methods increased infiltration and either had no effect or decreased sediment production (5). When running mesquite was treated with a herbicide and then burned, infiltration rates were not significantly increased (5). Sediment production on areas subjected to the herbicide/burning treatment also tended to be reduced compared to untreated plots, possibly a result of improved grass cover on the burned site.

RUNOFF AGRICULTURE

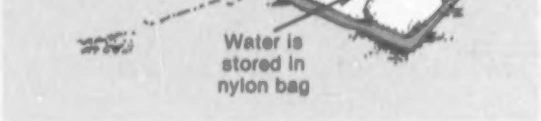
Introduction.—Because precipitation is infrequent in arid lands, farmers in lowland regions of the world have developed a variety of techniques to collect surface runoff for use in agricultural production. The theory behind these practices is that water can be collected from a large area and concentrated on a smaller, cultivated field for ample yields.

Historically, runoff agricultural systems allowed crop production in areas with as little as 4 inches of annual precipitation. When modern irrigation technology became available, many runoff agricultural systems were quickly replaced or abandoned and forgotten. Higher pumping costs for ground water, applicability to small-scale farming, availability of new building materials, and recent research on runoff agriculture have rekindled interest in the use of older technologies.

Runoff agriculture depends on water collection or "harvesting." Water-harvesting systems include two basic components: a catchment area for collecting rainwater and a water storage facility. There are many kinds of each (fig. 37). Selection of a particular method is determined by soil, topography, amount and pattern of precipitation, and climate.

Generally, water is collected on a soil surface that has been treated to make it impermeable. Treatments can include coats of paraffin wax, asphalt/fiberglass membranes, layers of sodium salts, gravel-covered plastic sheets, galvanized corrugated sheet metal, concrete slabs, or dense vegetative cover. Table 38 lists the features of some common catchment treatments.

Figure 37.—Catchment Surface With Butyl-Coated Nylon Water Storage Bag


Catchment surface
Water is stored in nylon bag

SOURCE: J. L. Thames and J. N. Fischer, "Management of Water Resources in Arid Lands," in *Arid-land Ecosystems: Structure, Functioning and Management*, vol. 2, D. W. Goodall and R. A. Perry (ed.) Cambridge, Mass.: Cambridge University Press, 1981), pp. 519-547.

Table 38.—Potential Catchment Treatments

Treatment	Runoff efficiency (percent)	Estimated life (years)	Initial cost ($/m²)
Land smoothing and clearing	20-35	5-10	0.01-0.06
Water repellents	60-85	5-8	0.15-0.20
Paraffin wax	60-95	5-8	0.30-0.50
Gravel-covered sheeting	75-95	10-20	0.40-0.60
Asphalt-fabric membranes	85-95	10-20	1.25-1.75
Concrete, sheet metal, artificial rubber	60-95	10-20	3.00-5.00

SOURCE: G. W. Frasier, "Water for Animals, Man, and Agriculture by Water Harvesting," G. R. Dutt, C. F. Hutchinson, and M. A. Garduno (eds.) *Rainfall Collection for Agriculture in Arid and Semiarid Regions*, (Sough, U.K.: Commonwealth Agricultural Bureaux, 1981), pp. 83-86.

Structures designed for other purposes, such as house roofs and roads, may collect water inadvertently, and this water can be used for agricultural purposes as well.

Collected water is stored in tanks or reservoirs. For many water-harvesting systems, the storage facilities are the more expensive item, but they are often vital to the success of a harvesting system. Typical storage facilities include butyl bags, steel tanks, and waterproof, excavated pits. It is possible that natural depressions such as playa lakes ("wet weather lakes") or preexisting storage facilities could be used also. Stored water is diverted to irrigate fields; directed into small basins around individual trees (microcatchments); or held temporarily behind a series of terraces.

An alternative practice to the use of catchment and storage facilities is "floodwater farming," whereby sporadic flashfloods that occur in watercourses of arid lands are managed to

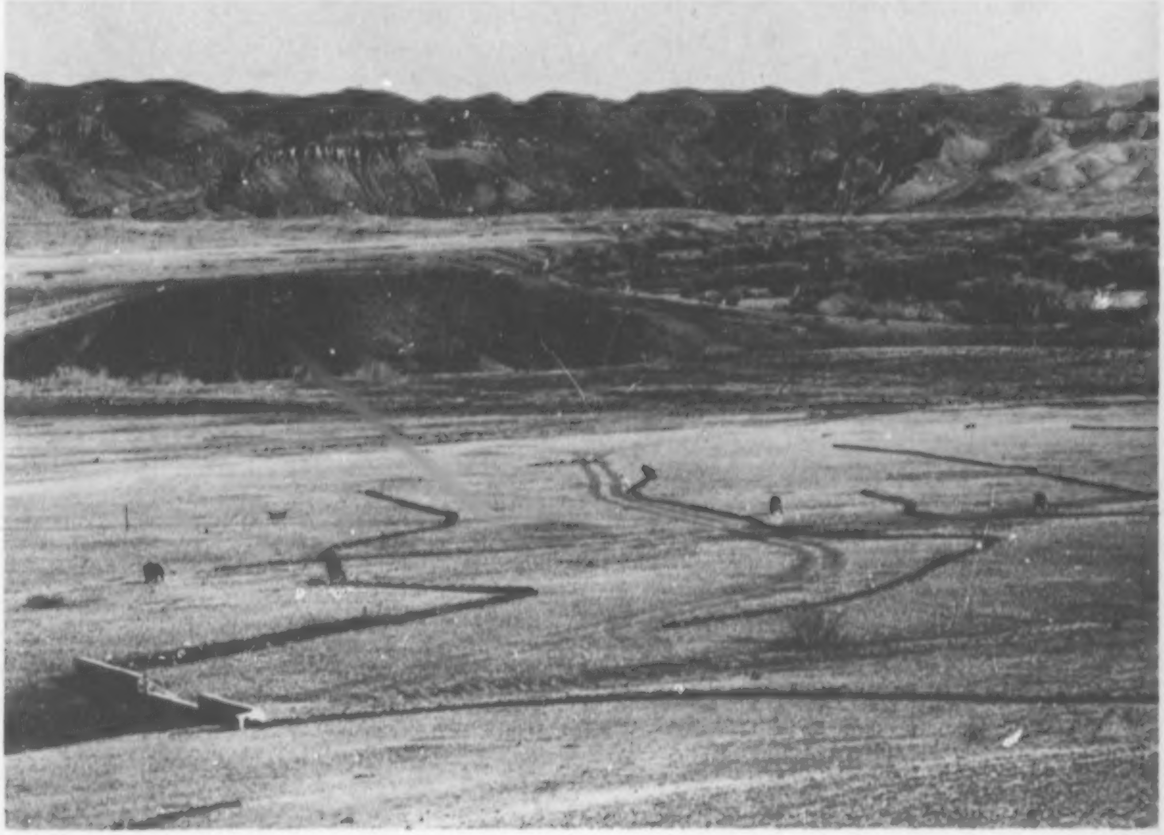


Photo credit: USDA-Soil Conservation Service

Masonry and water spreaders. Stock grazing on spreading area treated with rock percolators on contour supply water for crops. For example, crops can be planted in the bottom of intermittent watercourses, and dams can be used to control water when flashfloods occur; or crops can be planted at the point where intermittent watercourses spread into an alluvial fan.

Assessment.—A variety of crops can be grown using water obtained from surface runoff. Generally, crops need to be deep-rooted, drought-resistant, and suited to local soils, climate, and precipitation. The Papago Indians, for example, grow a number of vegetables using this practice, and some crops have been bred especially for this purpose. Other possible crops are jojoba, Christmas trees, tree fruits, grains, and wine grapes. Runoff agriculture can also be used to aid in establishment of plants that will not be harvested. For example, water-harvesting technology is being used in Mexico to aid in reseeding degraded rangelands.

Runoff agriculture systems that use water-storage facilities have been used extensively for animal watering to provide dependable sources of water for livestock and wildlife when other supplies fail. Some small systems that furnish water for wildlife in remote areas have been developed on public lands. Larger systems with both large catchment areas and storage facilities can provide water for several hundred head of livestock.

With current technologies, runoff agriculture has some physical, biological, and economic limitations. The systems depend on rainfall and are no more dependable than the weather. In areas with less than 2 to 3 inches (50 to 75 mm) of annual rainfall, costs of application and operation for water catchment and storage facilities may outweigh benefits of increased crop production. In addition, the high costs of these technologies restrict its use to small-scale applications such as livestock or wildlife.

Runoff agriculture systems also vary widely in their efficiency in collecting precipitation because of differences in soil, topography, climate, pattern of precipitation, and the materials used for catchment and storage facilities. Limited experience has shown that some catchment and storage facilities can collect 20 to 40 percent of precipitation. More elaborate systems can collect more than 90 percent.

Lifespan of the soil treatments is limited also, and replacement is costly. While these have improved greatly in recent years, the least expensive treatments still must be replaced every 5 to 10 years (table 39). Maintenance is often required because poorly designed and maintained facilities can cause soil erosion or local flooding. The site-specific nature of these facilities also contributes to their high cost. Each facility must be designed for its location and intended use.

Some scientists believe that with the rise in energy costs, runoff agriculture may compete more favorably with conventional sources of water. Questions remain, however; information is needed on the application of large-scale runoff systems on conventional agricultural crops and on the more complex effects of these systems on crops. For example, with jojoba it is known that runoff farming cannot be recommended when there is danger of severe, early frosts, since ample supplies of harvested water in the fall encourage growth that is very susceptible to spring freezing.

Questions have been raised also over the long-term effects of soil treatments on soil and water resources. Information on the quality of water from areas where the soil is treated is limited; some possibility exists that water from catchments could be contaminated by materials used for waterproofing.

Streamflow Forecasting

Introduction

Effective reservoir management requires some advance knowledge of both the timing and volume of runoff into the reservoir so that releases from the reservoir can be scheduled to meet identified demands and priorities most effectively. Runoff forecast technologies have been developed to facilitate acquisition of this knowledge.

There are two broad categories of streamflow-forecast technologies. First, some technologies forecast runoff resulting from rainfall by combining meteorological forecasting, soil-moisture accounting, and flow routing. Second, some technologies forecast spring snowmelt runoff from mountain watersheds. These involve an evaluation of the amount of snow present each spring at the beginning of the melt season, how the snow melts, and the way it enters the river system.

Technologies that forecast spring runoff are particularly important in light of the major role of this water source in meeting Western water demands. A variety of approaches to forecasting runoff from melting mountain snowpacks has been developed by Federal and State agencies responsible for various aspects of water resource development or management in the West. However, comparative analyses of these approaches are rare. Much of the following is adapted from Lettenmaier, et al. (15).

In the arid interior of the West, developers of the earliest water projects saw the potential for using winter snow depth measurements in the mountains as an indirect indicator, or "index," of runoff to be expected during the spring and summer snowmelt period. By the 1930's, a network of snow-measurement stations was established. With the expansion of the data base over time, forecasting methods have used an increasing number of indirect index indicators for predicting runoff—e.g., snow-course readings (the average of 10 individual measurements of a single site), winter precipitation at low-elevation stations, soil-moisture measurements, and areal extent of snow cover. In each case, attempts were made to relate statistically some easily measured variable, such as the water content of the snowpack at a point, to the complex of interactions that determined the volume and timing of spring snowmelt runoff.

With the advent of the digital computer, the level of detail that could be considered by numerical models of snowmelt and runoff physical processes was vastly increased. This prompted the development of simulation models of runoff and later of snow accumulation and melt processes. These models attempt to trace the fate of incident precipitation to its ultimate fate as streamflow, evaporation, or ground water recharge. Similarly, snowmelt (snow accumulation and melt) models attempt to simulate the history of water storage in a snowpack, including the melt process. Together, these models produce a simulated record of effective precipitation consisting of rain on bare ground and snowmelt. The record is used as input to a soil-moisture accounting model.

Photo credit: USDA-Soil Conservation Service

Snow surveyors weighing snow sample at Upper Wheeler snow course in Washington State

Simulation models are generally data-intensive and require an experienced user for successful implementation. They have been used for a variety of purposes, of which flood forecasting is one of the most important. However, they have also been used for seasonal runoff forecasting, notably by the California Joint State-Federal River Forecast Center and the National Weather Service (NWS) Hydrologic Research Laboratory.

The advantage for using conceptual models* is that they allow explicit consideration of such factors as soil moisture, which is not usually included in index models. They also allow convenient exploration of alternative scenarios. The Sacramento River Forecast Center, for ex-

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*For a discussion of water models in general, see the OTA assessment: *Use of Models for Water Resources Management, Planning, and Policy*, OTA-O-159, August 1982.

ample, was able to provide streamflow forecasts during the 1976-77 drought that were considerably more accurate than those achieved using index methods.

Institutional Responsibilities

Streamflow forecasting has been undertaken seriously for approximately the past 30 years. Responsibilities for runoff forecasting are dispersed among several Federal agencies, and, to some extent, each has developed its own approach to the preparation of a streamflow forecast. Only the NWS of NOAA and USDA's Soil Conservation Service (SCS) are mandated to disseminate forecasts publicly.

In the early 1930's, Congress provided funds and directed the Secretary of Agriculture to initiate a program of snow measurement to be used to estimate the amount of water expected to be available for irrigation use in the coming crop season. This cooperative snow survey and water supply forecast program was first assigned to the Bureau of Agricultural Engineering and later transferred to SCS, where it has remained since approximately 1950 (24).

Beginning in the late 1940's, the U.S. Army Corps of Engineers and NWS jointly undertook another program entitled the "Cooperative Snow Investigations Program." Its purpose was to initiate an interagency effort to develop the necessary tools for analyzing snowmelt runoff in connection with the respective authorities of the Corps of Engineers and NWS. It included contributions by other agencies, such as the Bureau of Reclamation and the U.S. Geological Survey (USGS) (18). This effort ultimately contributed to the development of the Streamflow Synthesis and Reservoir Regulation (SSARR) model, which is used by the Corps of Engineers and NWS in their joint reservoir-management activities in the Western United States, primarily in the Columbia River basin.

Working independently, in the 1940's NWS (then the Weather Bureau) began to develop short-term forecasting techniques and water supply forecast procedures (1). The Office of Hydrology of NWS began experimenting with continuous streamflow simulation models in 1964, leading to the creation of the NWS River Forecast System (NWSRFS).

Beginning in 1967, SCS initiated the use of a "parametric, deterministic, continuous watershed or basin simulation computer model" primarily to monitor average annual runoff and monthly runoff in several Western States. This model also included an estimation of water requirements of irrigated agriculture.

The National Aeronautics and Space Administration (NASA) in the mid-1970's began a research program designed around the ability of satellites to obtain imagery of various mountain snowpack properties. The primary focus is the area of the ground surface that is snow covered at different times of the accumulation and melt seasons. To date, research has relied heavily on the interpretation of the satellite imagery that relates snow-covered areas in the alpine belt to snowmelt-streamflow from an entire mountain range. Unfortunately, little of the satellite imagery data are readily available to the scientific community at large; thus, no broader use or independent verification is possible. In addition, given the cost of satellite imagery and the data processing required, the costs of this approach currently outweigh its benefits.

Also in the mid-1970's, USGS developed the Hydrometeorological Streamflow Prediction (HM) Method as another forecasting approach. In contrast to the more sophisticated attempts of NASA, this approach uses available low-altitude precipitation and runoff data from existing sites. Its primary advantage is the ease with which the data are obtained. The process of forecasting involves a simple accounting method based on precipitation inputs and runoff.

Assessment

Water-supply forecasting for either internal use or public dissemination is an activity in which at least eight Federal agencies and one State agency (California) are now engaged in the Western United States. This has resulted in some competition and confusion. For example, until the 1977 forecast season, both SCS and NWS prepared duplicate forecasts for 260 points in the West. In some cases, the forecasts proved to be significantly different, which resulted in some confusion among user groups. In 1978 those agencies entered a cooperative agreement to coordinate their activities and jointly produce and publish "Water Supply Outlooks for the Western United States."

A primary problem with the conceptual simulation models is the large amount of data required to use them and the relatively long computer running times involved (15). The USGS HM model achieves a balance between data requirements and the desirability of including some representation of physical processes in seasonal forecasts. This model represents forecast season runoff as the difference between total seasonal precipitation falling on the watershed and the sum of winter season runoff and other losses from the system. The seasonal precipitation is determined from measurements at low-elevation precipitation gages in the original HM model. This model has been modified to incorporate snow-course data (15). The relationship between inputs and losses from the system can be expressed also in terms of basin storage, in which forecast season runoff is taken to be winter storage less losses plus forecast precipitation.

The primary advantage of the HM model is that it reflects soil water/runoff interactions in a simple way, which is especially important in extremely dry years, since an accurate forecast is most valuable under extreme conditions, particularly droughts. It has been found that the most accurate runoff forecasts were acheived in extreme high and low runoff years. These are conditions under which the earlier methods perform most poorly, since the relationships used were often linear and most inaccurate when conditions were highly abnormal.

Improvement of runoff forecast accuracy is of practical importance only if it has some impact on water planning and use. The support of water users for water forecasting programs may be seen as some indication of the worth of the forecasts. For instance, SCS, in considering possible changes to its snow survey and water survey forecasting program, conducted a survey during 1979-80 of users of the program. Options included eliminating, continuing, or expanding the program. A large majority of the users supported continuation and/or expansion (15).

Various attempts have been made to evaluate forecast worth.* The most recent of these is the work of Castruccio , et al. (7), which provides estimates of the worth of forecast accuracy improvements throughout 11 of the Western States where snowmelt runoff is the primary source of surface runoff (tables 39 and 40). Five

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*Currently, there is no direct cost to the users for SCS forecasts, so it is not possible to employ a willingness-to-pay criterion to assess the worth of the information.

Table 39.—Summary of the Regional Irrigation Data and Benefits in the 11 Western States[a]

USGS hydrologic region	Benefit ($M)	Benefit/acre (in $/acre)	Percent total impacted irrigated acreage	Estimated average annual crop value/ acre ($/acre)
Missouri	$7.1	$1.14	30.9	$195
Arkansas Red-White	0.9	1.69	2.6	307
Rio-Grande	1.4	3.61	2.0	408
Upper Colorado	1.1	0.86	6.2	184
Lower Colorado	0.8	8.53	0.4	642
Great Basin	2.8	1.56	8.7	209
Pacific Northwest	7.0	1.17	29.5	293
California	5.5	1.39	19.7	592

[a] The 11 Western States are: Arizona, California, Idaho, Colorado, Oregon, Washington, Montana, Wyoming, New Mexico, Utah, and Nevada.

SOURCE: P. Castruccio, H. Loats, D. Lloyd, and P. Newman, *Applications Systems Verification and Transfer Project, Volume VII: Cost/Benefit Analysis for the ASVT on Operational Applications of Satellite Snow-Cover Observations*, National Aeronautics and Space Administration Technical Paper 1828, 1981.

Table 40.—Summary of Computed Hydroelectric Energy and Other Relevant Data by USGS Hydrologic Region

USGS hydrologic region	Benefit (V_{IF}) $M	Benefit/MWh ($/MWh)	1978 percent of total hydroelectric energy production (percent)	Current[a] difference between hydroelectric & steamelectric energy production (mills/kWh)	Current[a] difference between 1° & 2° revenues from the sale of energy (mills/kWh)	Streamflow forecast error (percent)
Missouri	1.0	0.17	3.2	7.70	21.43	27.5
Arkansas Red-White	0.05	0.18	0.1	7.73	21.41	29.0
Rio Grande	0.1	1.03	0.1	17.57	19.16	43.8
Upper Colorado	1.1	0.2	3.2	6.50	23.89	24.2
Lower Colorado	2.1	0.46	2.5	18.07	15.33	89.9
Great Basin	0.1	0.24	0.3	19.36	4.36	39.4
Pacific Northwest	3.8	0.03	73.1	7.57	3.63	11.9
California	1.9	0.06	17.7	26.08	6.69	10.0

[a] Values shown have been adjusted for inflationary rises on production expenses (inflationary factor = 1.21) and sales revenues (inflationary factor = 1.26).

SOURCE: P. Castruccio, H. Loats, and D. Lloyd, and P. Newman, *Applications Systems Verification and Transfer Project, Volume VII: Cost/Benefit Analysis for the ASVT on Operational Applications of Satellite Snow-Cover Observations*, National Aeronautics and Space Administration Technical Paper 1828, 1981.

water uses that might be affected by water-supply forecasts have been identified: hydroelectric energy generation, irrigated agriculture, municipal and industrial uses, navigation and recreation, and fish and wildlife (7). Of these, hydroelectric energy generation and irrigated agriculture were identified as being by far the most economically significant. In considering an arbitrarily selected forecast improvement of 6 percent over the existing situation, these authors found a wide range of economic benefits for the individual water subregions of the Western United States. The economic benefit was found to be related to both the accuracy of present forecasts and the value of agricultural products or electrical energy produced by the water. For irrigated agriculture, they projected increased economic values ranging from $0.32 to $12.33 per surface water-irrigated acre. The highest values were found for the Lower Colorado River Basin, where forecast accuracy is low and the value of crops produced by irrigated agriculture is high. The lowest values came from the Pacific Northwest, where forecast accuracy is relatively good. The economic benefit for hydroelectric energy generation was calculated to range from $0.03 to $1.03 per million watt-hour (MWh). They calculated that the annual economic benefit for the 11 Western States resulting from a 6-percent increase in forecast accuracy for irrigated agriculture would be $26,476,739 and for hydroelectric energy generation, $10,032,798. These benefits are summarized in tables 39 and 40.

Improvement of streamflow forecast accuracy, in general, is dependent on a number of factors, including forecast technology, watershed characteristics, climatic conditions, and data availability and reliability. In some cases, where adequate data are available and existing forecast methods are based on the development of a simple statistical relationship between some variable, such as snow water-equivalent depth, and annual runoff volumes, it may be possible to achieve forecast improvements of at least 25 percent over existing methods (15). More commonly, improvements in the range of 10 percent appear to be a more reasonable estimate. As noted above, even this modest improvement has the potential for producing a considerable economic benefit by improving the management efficiency of the reservoir system of the Western United States.

Water-supply forecasting would benefit from an increased understanding of the highland watershed environment. It would also benefit from increased coordination and cooperation among the various Federal and State agencies involved, primarily to eliminate any areas of duplication. Primary research efforts could be directed toward improving the ability to forecast the timing of the annual spring runoff. Forecasts of annual volume are reasonably accurate for most of the forecast techniques, although some effort could be expended in obtaining small increases in this accuracy. It has been suggested that even small increases in the forecasts of streamflow volume for certain regions in the Western United States would have considerable economic benefit for agriculture.

CONCLUSIONS

Three major categories of technologies (weather modification, watershed management, and streamflow forecasting) have evolved to estimate and manipulate the surface runoff produced annually or seasonally by precipitation on watersheds in the Western United States. Debate and uncertainty exist in each of these categories regarding their effectiveness and potential.

The two weather-modification technologies that have received the most attention are those involving: 1) winter storms that cross the major mountain ranges of the Western United States, producing the snowpack of the mountain watersheds, and 2) the summer cumulus clouds that produce rain and hail, often in large amounts over limited areas. While "seeding" these air masses could produce additional precipitation under the right conditions, more research is needed on whether this reaction results in increased soil water or surface runoff in the target area. Additional information is also needed on the physical interaction between the artificial nucleating agent and the existing physical properties of an air mass and on the development of acceptable verification criteria for evaluating the success of a cloud-seeding experiment.

Watershed-management technologies are designed to manipulate the water resource once precipitation has reached the ground for onsite or offsite use. In the Western United States, the most important of these technologies from the standpoint of volumes of water are those intended to increase surface runoff from the highland mountain snowpack.

The most water productive of all the major biophysical environments of the region is the alpine zone, that zone in the highest elevations of the major mountain ranges. This zone has received little scientific attention. The few alpine studies suggest that a conservative, passive-management approach may be the most beneficial technology for the present.

Technologies that affect the montane zone have involved, to a great extent, the removal of all or portions of the mountain forest in an attempt to alter snow-accumulation patterns, evapotranspiration losses, or rates of meltwater production. It has not yet been established that forest removal will result in predictable runoff increases for downstream arid/semiarid agriculture.

Attempts to modify the surface runoff regime in lowland watersheds involve a wide range of technologies, depending on the specific environment involved and possible objectives. In some cases, the production of increased runoff is desired; in others, the retention of water for onsite uses is the goal. Generally, the approach is to modify vegetation or the physical surface area of the site. Results in these regions have been variable because of the different objectives and because of natural variations in lowland watersheds.

Water-supply forecasts are undertaken by several Federal and some State agencies to improve regulation of reservoirs that control the surface flow of Western rivers. These efforts sometimes are not coordinated and include aspects of duplication and inconsistency. A wide range of forecast models exists, from very sophisticated, computed simulation technology to simpler statistical correlation models. Research has indicated that no single forecast model is sufficient for all hydrometeorological environments in the West. In general, those models having the simplest data and computer processing requirements would appear to be most desirable, strictly from local use, economic, and efficiency standpoints. An example of this type of model is USGS's HM model. Attempts are being made also to incorporate satellite imagery and data acquisition by remote telemetry into the data input required for forecasting. Much improvement is possible in forecasting techniques to assist in more effective water-resources planning and management for all Western users, including the major user, agriculture.

Each technology assessed in this chapter has demonstrated that it can, at least on a local, site-specific basis, either augment runoff from mountain watersheds or forecast the volume of that runoff. In every case, however, it has proven difficult to demonstrate that the results can be generalized over extensive areas. Of the technologies to augment runoff, precipitation augmentation from winter orographic storm systems by "cloud seeding" appears to show the most potential. This technology, while not living up to some of the claims of its more enthusiastic supporters, has been developed within a solid scientific framework that has created a body of knowledge that should facilitate future studies. Watershed management, on the other hand, has been approached largely as an adjunct of commercial logging operations. For this reason, the relationship between deforestation or afforestation and water yield from highland watersheds is much more speculative. This entire subject area would benefit from a more rigorous scientific approach emphasizing water yields rather than timber production if it is to be given serious consideration as a technology capable of producing additional water for Western agriculture. Technologies for the management of lowland watersheds to increase water yield can be applied locally (e.g., to produce water for stock ponds), but in general they cannot create sufficient additional runoff to affect regional supplies, except in exceptional circumstances.

Water-supply forecasting is gradually developing approaches based on more realistic models and more sophisticated data collection techniques. Water-supply forecasting technologies should form the foundation of water management and planning in the Western United States. As such, responsible Federal agencies should be encouraged to evaluate critically the existing forecast systems, to develop a more detailed study of the processes controlling snow accumulation, melt, and runoff from highland watersheds; and to coordinate their efforts with those involved in precipitation augmentation and watershed-management technologies.

Finally, a more coordinated approach to the study and management of highland hydrologic systems would greatly benefit each of the technologies discussed in this chapter. Ideally, the goal of this effort would be the development of an ability to trace the path and history of water from the time it originates as augmented precipitation in a winter orographic storm through deposition, melt and ultimate runoff into either the rivers or reservoirs of the region, and evapotranspiration or percolation to ground water.

CHAPTER VI REFERENCES

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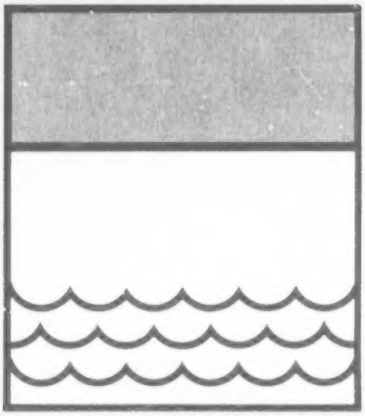

VII

Technologies Affecting Surface Water Storage and Delivery

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Chapter VII

Technologies Affecting Surface Water Storage and Delivery

In the Western States, where demand for water often exceeds supply, additional surface water can be made available by: 1) increasing the total amount of water in storage, or 2) conserving existing water supplies. Conservation methods, which can often be applied relatively easily, hold promise for short-term changes in water use. Methods that increase the amount of water in storage require significantly larger investments of time and money and may take generations to implement.

This chapter considers a variety of technologies that affect surface water storage and delivery. Methods that increase the total amount of water in storage include desalination, interbasin transfers, and new water projects. Several commonly discussed water-conservation technologies are also discussed including flexible irrigation delivery systems, seepage and evaporation control, and vegetation management.

This chapter focuses on those technologies that have potential for sustaining supplies of surface water. The effects of widespread adoption of these practices by agricultural producers, however, are difficult to judge, and quantitative analyses are lacking. Debate continues regarding their technological potential, their economics of use, and the legal and social implications of their application.

THE WATER SETTING

Natural streamflow and precipitation seldom meet agricultural demands for irrigation, household, and stock water in U.S. arid and semiarid regions. Therefore, Native Americans and settlers devised various ways to manage their water supplies early in U.S. history. Some of these methods were relatively simple and involved collecting precipitation and runoff for use when other water sources failed (see discussion of runoff agriculture in ch. VI). Later, more elaborate systems of reservoirs and canals were built to store runoff, sustain downstream flow during dry periods, and convey water to irrigation users. Also, multipurpose reservoirs were built to control floods, maintain fish and wildlife habitat, and supply electrical power and recreation.

These and other developments have altered the hydrologic cycle. Series of large reservoirs now regulate the amount and timing of surface water flow for much of the length of several Western river systems. Natural runoff has been reduced by 100 million to 150 million acre-ft annually (ch. III). Smaller scale developments also have affected surface water quality. Some methods for restoring riparian vegetation decrease sedimentation and increase water storage. Changes in ground water use have also affected surface waters. Ground water pumping from the Ogallala aquifer has lowered water tables and decreased surface water flow in Nebraska and western Kansas.

THE TECHNOLOGIES

Technologies That Augment Water Supplies

Storage Facilities

INTRODUCTION

Three Federal agencies have authority over the extensive system of Western water-storage facilities. The U.S. Army Corps of Engineers and the Department of the Interior's Bureau of Reclamation are charged with developing, managing, and conserving water resources. Both agencies' missions include supplying water for municipalities, industry, irrigation, recreation, hydroelectric power, and fish and wildlife. In addition, the Corps, builds and operates projects for flood control, hurricane protection, and navigation. The Bureau of Reclamation, initially authorized to provide irrigation water, operates only in the 17 Western States.

In addition to these groups, the Soil Conservation Service of the U.S. Department of Agriculture encourages development of small watershed projects for soil and water conservation and flood control. The U.S. Geological Survey maintains a large collection of data on hundreds of lakes, reservoirs, and other surface waters. Finally, State governments have built storage facilities. For example, California designed, financed, built, and operates one of the world's largest multiple-purpose reservoirs at Oroville Dam.

A complex system of both large and small reservoirs exists as a result of these water-development projects. The reservoir storage capacity in the Western river basins is about 79 percent of the U.S. total (table 41). These storage facilities include a few very large dams and reservoirs that contribute much of the total storage capacity, a sizable number of medium-sized reservoirs, and even more farm and ranch ponds (table 42).

These reservoirs are managed to permit more convenient and efficient use of available water

Box L.—Dams and the Western Spirit

Stored water: to some it makes the desert bloom; to others it is sacrilege. Our feelings about dams reflect our most fundamental values:

> **Hoover Dam, show piece of the Boulder Canyon project, the several million tons of concrete that made the Southwest plausible, the *fait accompli* that was to convey, in the innocent time of its construction, the notion that mankind's brightest promise lay in American engineering. Of course the dam derives some of its emotional effect from precisely that aspect, that sense of being a monument to a faith since misplaced . . . .—Joan Didion, 1970**
>
> **Growing up on a farm that had been homesteaded by his grandfather in the eighteen-seventies, [Bureau of Reclamation Commissioner] Dominy often enough saw talent and energy going to waste under clear skies . . . . When Dominy was eighteen years old, a big thing to do on a Sunday was to get into the Ford . . . and go out and see the new dam. Eventually he came to feel that there would be, in a sense, no West at all were it not for reclamation.—John McPhee, 1971**

SOURCES: Excerpted from: Joan Didion, "At the Dam," *The White Album* (New York: Simon & Schuster, Inc., 1979), 1970, p. 199. John McPhee, *Encounters With the Archdruid* (New York: Farrar, Straus & Giroux, Inc., 1971), pp. 158-159.

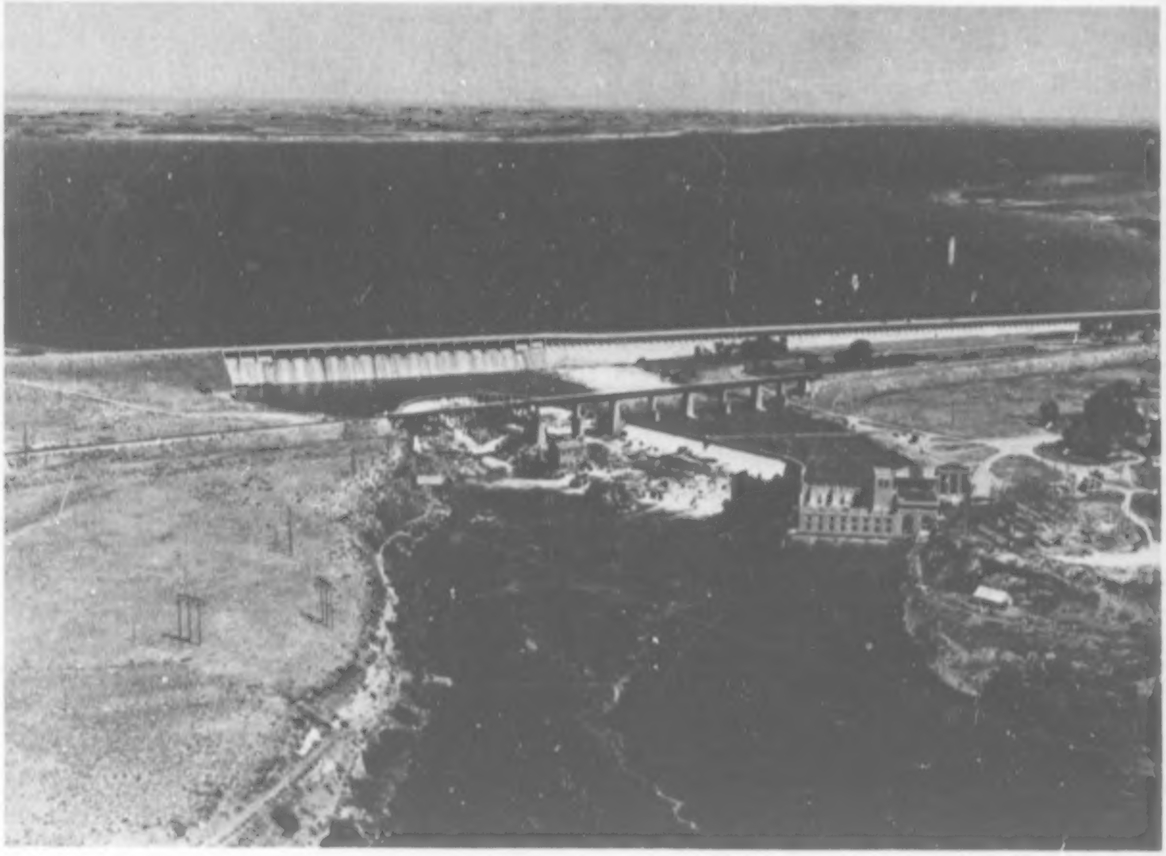


Photo credit: USDA-Soil Conservation Service

The American Falls Dam and reservoir stores 1,700,000 acre-ft of water. It was constructed in 1925 near Pocatello, Idaho

Table 41.—Reservoirs in the Western River Basins With at Least 5,000 Acre-ft of Storage Capacity

Region	Number of reservoirs	Natural flow	Storage capacity (000 acre-ft/yr)	Evaporation losses (000 acre-ft/yr)	Other losses
Rio Grande	23	2,670	3,958	816	53
Arkansas-White-Red	14	1,440	1,321	113	48
Missouri	105	23,880	26,005	1,108	57
Upper Colorado	40	15,130	33,083	766	209
Lower Colorado	27	2,650	35,883	1,369	—
Great Basin	48	8,350	4,237	1,645	204
California/South Pacific	221	75,890	36,931	1,323	4,148
Columbia/North Pacific	201	248,350	42,734	4,577	4,896
Texas-Gulf	0	10	0	12	—

SOURCE: U.S. Department of the Interior, *Critical Water Problems Facing the Eleven Western States* (Washington, D.C.: U.S. Government Printing Office, April 1975), pp. 43, 45-46, tables II-28-30.

Table 42.—Features of U.S. Reservoirs

Reservoir size (1,000 acre-ft)	Number	Storage capacity (1,000 acre-ft)	Part of total U.S. storage (percent)
More than 10,000	5	117,000	25
2,000 to 10,000	26	74,000	16
5 to 2,000	1,600	168,000	37
0.05 to 5	47,500	91,000	20
Less than 0.05	1,843,000	10,000	2
Total	1,892,131	460,000	100

SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 2, pt. IV, table IV-3.

supplies by downstream users. They may be used in conjunction with other surface or ground water facilities such as pumps, pipelines, wells, and canals. Both large and small facilities may have multiple uses. For example, farmers and ranchers sometimes store water for frost control, fire protection, domestic use, spraying fertilizers or pesticides, or recreation.

Onfarm irrigation reservoirs are used to:

1. store runoff for use during dry periods,
2. store water during periods of low demand or at times when irrigation is not possible,
3. store water overnight,
4. regulate flows or otherwise match elements of an irrigation system,
5. store irrigation runoff, called "tailwater," and
6. control water levels in adjacent areas.

Ranches often have small stock-watering reservoir systems developed from natural or artificial impoundments. These may be used to increase stocking rates by: 1) lengthening the grazing season, 2) spreading use more evenly over the range, or 3) opening new land to grazing.

ASSESSMENT

Construction technologies for large and small reservoirs are well developed. Recent advances include the use of rolled concrete and soil cement and improved methods for placing cutoff walls. Modern dams are safer and more durable than their early 1900 counterparts. Technologies to manage reservoirs are advancing rapidly. New means exist to gage and time water flows and to monitor water movement throughout even the largest river systems. In order to assess the future of surface-water storage facilities, therefore, it is necessary to look beyond available technology.

Photo credit: USDA-Soil Conservation Service

This 33-ft-diameter stock-water tank supplies ground water for two herds of cattle near Sterling, Colo.

The Federal Government is a major reservoir owner as a result of past investments. For example, the Federal Government owns over 2,000 dams, ranging in size from small diversions to huge multipurpose projects such as the Central Valley Project in California. In addition, 50-percent Federal cost-sharing spurred farm- and ranch-pond construction; by 1964, one-fourth of all U.S. farms and ranches had privately owned ponds, pits, reservoirs, or earthen tanks. Over 2 million such structures were built, but they were not heavily concentrated in the West (15).

The Federal Government [illegible] an investment of more than $28 billion in completed water-resource projects and annual construction and rehabilitation costs for the federally owned

Box M.—Managing the Columbia River: CROHMS

The Columbia River Operation Hydromet Management System (CROHMS) is an example of the integrated management of a river and its reservoirs to produce a more efficient use of the region's water. It is based on new and advanced technology: a central computer with access to hydrological data gathered throughout the Columbia River Basin, data processors and displays, and mathematical models of river and reservoir behavior. Taken together, these components simplify decisionmaking on reservoir management at 80 dams used for hydroelectric power generation, flood control, irrigation water supplies, and recreation.

A number of independent data-collection systems forward information to CROHMS, where data is processed and made available to all potential users. Cooperating Federal agencies include the Bonneville Power Administration, the U.S. Army Corps of Engineers, the Bureau of Reclamation, the National Weather Service, the Geological Survey, and the Soil Conservation Service (SCS). The Province of British Columbia also participates. Several U.S. agencies collect and provide data from remote weather stations such as SCS Snotel and Bonneville's Hydromet. The computer software is another important aspect of CROHMS. These programs are still under development at the center in Portland, Oreg., but they will eventually include a complex data-management system, methods for data validation, and various mathematical models for forecasting streamflows and reservoir regulation. Eventually, automation will virtually eliminate the cumbersome manual tasks of preparing data for the computer.

CROHMS represents an attempt to forecast and regulate the flow of a major river system by computerized data collection, analysis, and modeling. If successful, this approach should improve the efficiency with which the water in a river basin can be managed. This, in turn, should make more equitable the allocation of water among potentially competing users.

SOURCE: Speer, et al., "CROHMS—An Example of Successful Interagency Coordination in Data Collection," *47th Annual Meeting, Western Snow Conference* (Reno, Nev., 1979), pp. 102-107.

projects are high. In fiscal years 1981 and 1982, combined appropriations for the Army Corps of Engineers and the Bureau of Reclamation for these purposes totaled $1.7 billion and $1.9 billion, respectively. Only a portion of the Corps' budget was spent in the West, but the entire Bureau of Reclamation budget is related to Western water developments. Long-term U.S. Treasury borrowing finances these projects almost totally (39).

The benefits of these expenditures have been sizable. The larger projects made it possible to plan, build, and finance works on the scale required for main-stem Western rivers. Sometimes these have provided irrigation water, higher farm incomes, flood control, municipal water supplies, reservoir recreation, and power generation. For example, irrigation has made agricultural land use more productive on a per-acre basis.

There have also been substantial costs in addition to those noted above. Scenic and productive lands have been inundated, capital and labor have been diverted, families and towns have been displaced, fish and wildlife habitat has been altered, and towns have faced "boom town" social problems.

In the past, these large, federally funded water projects were approved on an ad hoc basis and met with little opposition (7). This situation no longer exists. Project selection, authorization, and construction now receive increased attention (see ch. V).

Barriers to new large-scale developments are physical, economic, and environmental. The physical sites most suitable for large-scale storage facilities have been used. The remaining sites may be less favorable for large dam construction and more distant from major population centers, thus decreasing their value for recreation, an important benefit for multiple-purpose projects.

The economic costs of large projects have escalated, making conservation, improved management, and other nonstructural methods more attractive for making more water available. In addition, the economic costs and benefits of existing projects have been called into question. The analytical techniques used by project sponsors to determine costs, associated benefits, and interest and payback rates from users sometimes have been criticized as inaccurate and misleading (8,38).

Also, today it is clear that large reservoir construction may result in major environmental effects and hazards (tables 43 and 44). Development around Lake Powell, for example, has increased air pollution, noise pollution, and litter (19). The majority of dams and reservoirs in many States became operational in the early part of the 1900's. Because previous water planners focused on project construction, not operation and maintenance, many expenditures to ensure the safety and efficient management of old facilities have been postponed. The total cost of these repairs could reach several billion dollars (39).

Because of these constraints, many experts expect that the Federal role in building and operating new large-scale water projects will decline sharply. New storage facilities are likely to be smaller, and their construction may depend entirely on private or non-Federal public investment or innovative cooperative arrangements between private and public developers or among Federal, State, and local governments. State bonds, revenue-sharing, property taxes, user charges, and joint ventures may become alternative means of raising funds. In Wyoming, for example, when the State Engineer declared a reservoir unsafe if more than one-half full, private investors agreed to renovate the reservoir in return for the first new 5,000 acre-ft of storage (1).

It is not clear to what extent farmers and ranchers will be able to take advantage of arrangements such as these. If Bureau of Reclamation irrigation projects that are based on irrigators' ability to pay contribute only about 19 percent of all costs, it is unlikely that private financing at higher levels will be profitable (17,28). The hydrologic effects are also not well known. The trend to construction of a larger number of smaller reservoirs may reduce the amount of water stored throughout the region.

Table 43.—Changes in the Colorado River, Grand Canyon National Park, as a Result of Glen Canyon Dam

Feature	Pre-dam	Post-dam
Appearance of water	Red	Green
Average annual sediment load	140 million tons	20 million tons
Annual variation in water discharge	High, seasonal	Low, daily
Annual water temperatures	32-85° F	42-48° F
Light penetration	1-2 inches	River bottom

SOURCE: S. W. Carothers and R. Dolan, "Dam Changes on the Colorado River," *Natural History*, vol. 91, 1981, pp. 75-83.

Table 44.—The Effects of Glen Canyon Dam on Animal and Plant Life in the Colorado River, Grand Canyon National Park

	Results	
Alteration	Increases	Decreases
Water discharge	Streamside plants, animals	Wetland breeding habitat
Light penetration	Mats of green algae	
Water temperature	Exotic fish (19 species)	Native fish (8 species)
Overall changes	Complex terrestrial food webs	Complex aquatic food webs

SOURCE: S. W. Carothers and R. Dolan, "Dam Changes on the Colorado River," *Natural History*, vol. 91, 1981, pp. 75-83.

With higher surface to volume ratios, these reservoirs might lose larger percentages of their water by evaporation and seepage.

Desalination

INTRODUCTION

As municipalities, industries, and irrigated agriculture continue to grow, demand for freshwater is expected to increase in the arid and semiarid regions of the West. Desalination is one technique that can supplement freshwater supplies by removing salt from ocean water or by improving the quality of salt-degraded water. In some cases, complete desalination may not be necessary. Salt-tolerant plants (ch. IX) and corrosion-resistant hardware may allow brackish water to be used. In addition, saltwater or desalination wastes may have direct uses. For example, some solar-powered greenhouses use saline water for heating and cooling. Moreover, seafood aquaculture depends on saltwater (ch. XI), and salt-gradient solar ponds can supply economical electricity and heat (12).

Of the many desalting techniques that exist, there are four general methods: 1) distillation, 2) membrane processes, 3) crystallization, and 4) chemical processes (table 45). General desalting operations are similar (fig. 38). Water is delivered and mechanically screened to remove suspended solids and debris. Subsequent processing results in two products: a disposable brine stream and a product stream which may be treated further, depending on its intended use.

Desalting plants exist throughout the world and are located in arid, semiarid, and humid climates. They range in capacity from a fraction of an acre-foot to hundreds of acre-feet per day. In the United States, a reported 637 plants produce 760 acre-ft/day or approximately 15 percent of the worldwide output (table 46). One-half of these plants are located in California, Florida, Texas, and Arizona.

One of the largest U.S. facilities will be the Bureau of Reclamation's Yuma (Ariz.) desalting plant. Scheduled to be operational by the end of 1987, it will produce 0.1 million acre-ft of water per year using a membrane process (18). The plant will treat Colorado River water before it passes to Mexico, as required by treaty.

Table 45.—Methods of Converting Saline Water to Freshwater

Distillation processes:
Examples:
- Multistage flash distillation
- Vertical tube distillation
- Multieffect multistage distillation
- Solar humidification

Attributes:
- Most widely used
- Energy intensive and costly
- Results in "ultrapure" water
- Favored for seawater

Membrane processes:
Examples:
- Reverse osmosis
- Electrodialysis
- Transport depletion
- Piezodialysis

Attributes:
- Favored for brackish water
- Require pretreatment to remove pollutants
- Potentially energy efficient
- Increasingly popular

Crystallization processes:
Examples:
- Vacuum freezing-vapor compression
- Secondary refrigerant freezing
- Eutetic freezing
- Hydrate formation

Attributes:
- Experimental stage
- Minimize corrosion
- Potentially energy efficient
- High recovery without major pretreatment

Chemical processes:
Example:
- Ion exchange

Attributes:
- Less costly "ultrapure" water
- Useful for low-salinity water

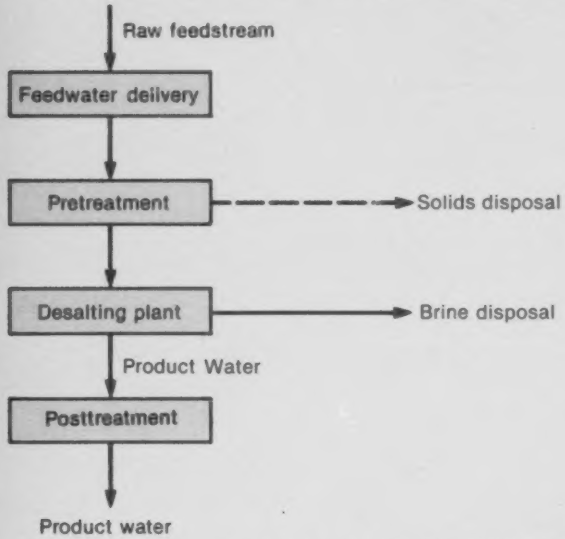
SOURCES: U.S. Department of Interior, The A-B-C of Desalting (Washington, D.C.: U.S. Government Printing Office, 1977), p. 2. U.S. General Accounting Office, "Desalting Water Probably Will Not Solve the Nation's Water Problems, But Can Help" (Washington, D.C.: General Accounting Office, CED-79-60, 1979).

ASSESSMENT

Desalination by many methods is technically feasible, at least for small amounts of water. It has proven to be a reliable way to meet specialized water needs but requires further development before it can produce low-cost freshwater.

High costs are the major current limitation to use of desalination, although brine-disposal

Figure 38.—General Scheme of a Desalting Plant



SOURCE: Catalytic, Inc., *Desalting Handbook for Planners* (Washington, D.C.: U.S. Department of the Interior, OWRT TT/80 3, September 1979), p. 3-2, fig. 3-1.

Table 46.—Desalting Plants, by Location

Region	Number of plants	Plant capacity (acre-ft/day)
United States	637	760
U.S. Territories	34	78
North America (outside U.S.)	58	51
Central America and Caribbean	66	123
South America	41	30
Great Britain and Ireland	63	51
Europe	256	380
Africa	244	438
Arabian Peninsula and Iran	599	3,485
Asia and India	172	292
Australia and the Pacific	19	9
U.S.S.R.	18	202
All regions	2,207	5,899

SOURCE: Techno-Economic Services, *Desalting Plants Inventory Report No. 7* (Honolulu, Hawaii: Techno-Economic Services and Ipswich, Massachusetts: Water Supply Improvement Association, May 1981), p. 9, table 1.

problems also could be troublesome. Costs and conversion rates for the various desalting processes vary widely. They include capital costs based on the process type, plant capacity, feedwater type and salinity, pretreatment required, product salinity, site-related costs for land, and operating, maintenance, and replacement costs.

These considerations limit production of desalted water to municipalities and industries and exclude most agricultural uses (5). For example, desalted municipal water costs about $1,300/acre-ft for seawater and $325/acre-ft for brackish water. Municipal water from conventional sources costs about $13/acre-ft (37). Some irrigators pay $0.27 to $9.82/acre-ft of water (39).

Use of expensive desalted water for irrigation would seem feasible where high-value, high-yield crops could be grown under a year-long or nearly year-long growing season, or where no other water was available. Under such conditions, farmers could take advantage of the year-round water production from a capital-intensive desalting plant. Precise farm delivery and crop application would be required because of the high water costs. Where desalination is required because of agricultural salt buildup (e.g., the Yuma plant), agriculture cannot carry desalination costs alone.

Interbasin Transfers

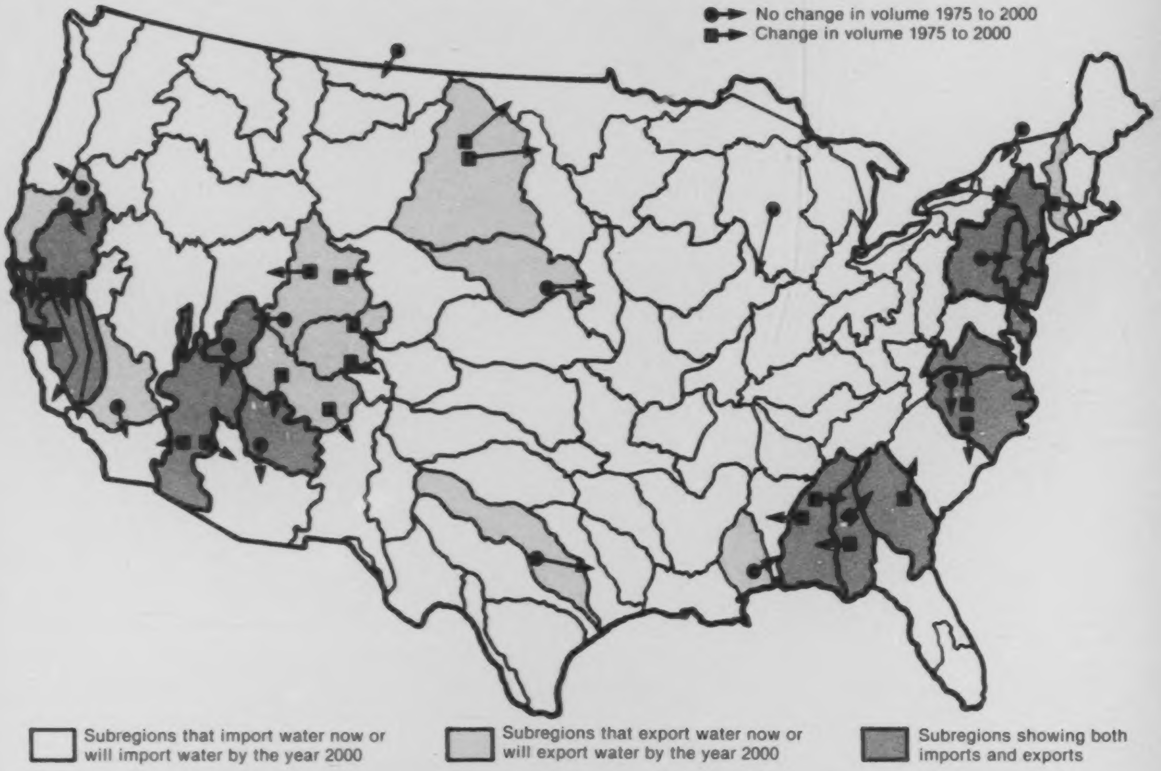
INTRODUCTION

Water transfers from one river basin to another for irrigation, municipal and industrial use, hydroelectric power, and other purposes have existed throughout the world for centuries. In the Western United States, regional transfers of water from the Colorado River Basin to other basins—e.g., the Colorado-Big Thompson Project—have been in operation for many years (fig. 39). Current attention focuses on proposals to transfer water from areas of supposed surplus (e.g., Alaska, the Missouri River) to Western stream systems for irrigation use.

ASSESSMENT

Results of the recently completed Six-State High Plains-Ogallala Regional Resources study, authorized by Congress in 1976, highlight the complexity of the interbasin transfer issue. As part of the overall study, Congress directed the U.S. Army Corps of Engineers to investigate the potential for augmenting water supplies in

Figure 39.—Water Imports and Exports


No change in volume 1975 to 2000
Change in volume 1975 to 2000
Subregions that import water now or will import water by the year 2000
Subregions that export water now or will export water by the year 2000
Subregions showing both imports and exports

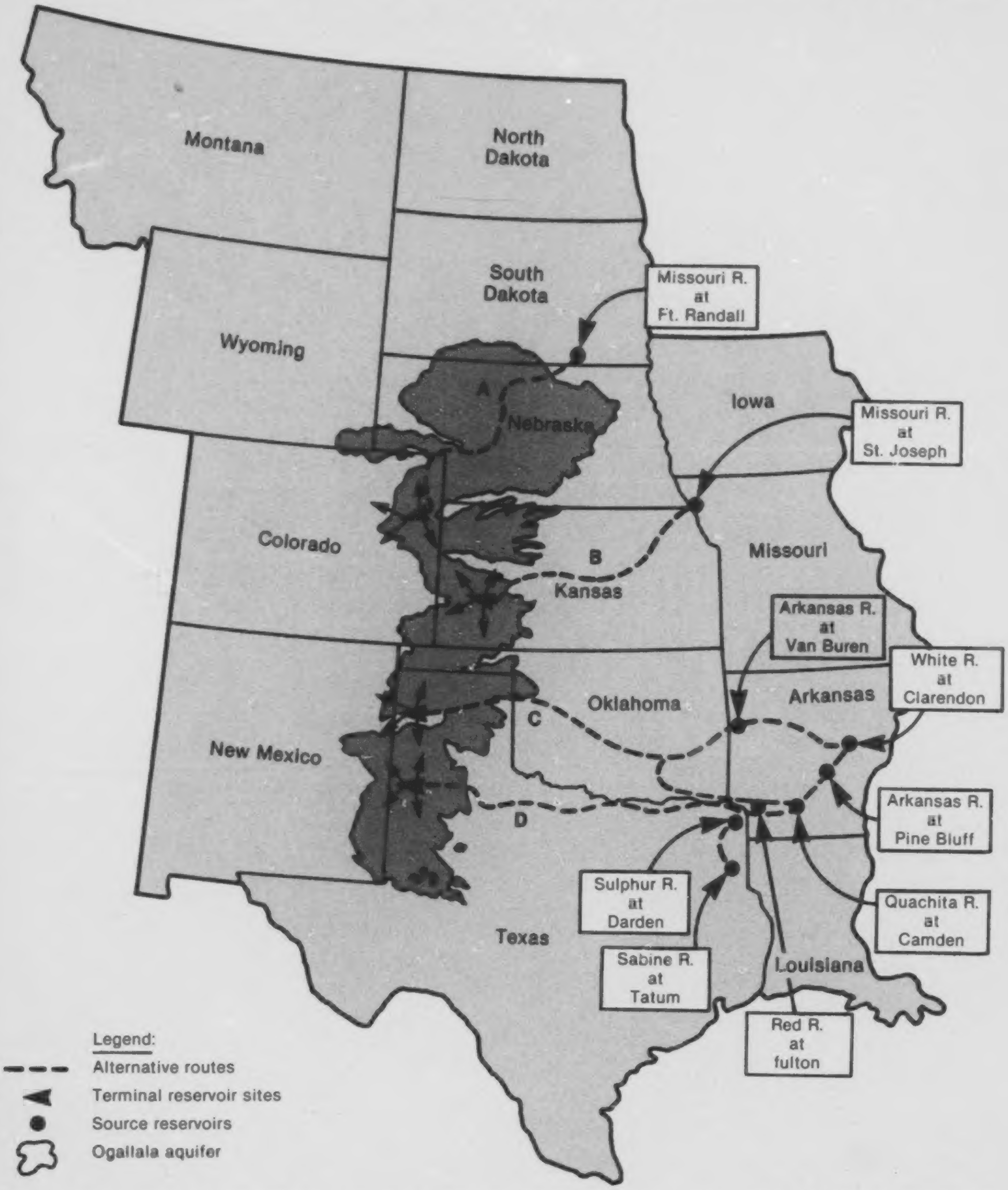
Water transfers occur throughout the United States, both within water resource regions and between regions. This illustration shows where water imports and exports occurred in 1975 and are projected for 2000. The estimates of future increases or decreases in transfers are based on authorized and/or funded projects only.

SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 2, pt. IV, p. 15, fig. IV-6.

the region through interbasin transfers from "adjacent areas." The Corps examined four plans in detail. Two proposed to divert water from either Fort Randall, S. Dak., or St. Joseph, Mo., on the Missouri River and convey it to eastern Colorado or Dodge City, Kans. Two other proposals considered tapping water at various points along the Arkansas, White, Ouachita, and Red Rivers in Arkansas and the Sulphur and Sabine Rivers in Texas and transferring this water to storage points in Texas (fig. 40).

The Corps concluded that construction of canal systems capable of transporting 9 million acre-ft of water was feasible from an engineering standpoint. However, there were numerous economic, physical, and environmental barriers to implementation (2). First, the cost of irrigation water obtained from an interbasin transfer was prohibitively expensive and ranged from $226 to $434/acre-ft (1977 dollars), exclusive of costs beyond the terminal reservoir. Furthermore, with the high energy requirements needed for operation, water costs were projected to escalate significantly as energy costs increased. Second, no surplus water existed in the basin of origin, given present and future needs of the source basin. Third, construction of any of the routes would result in major environmental impacts. These projected effects included altered flow regime of the source streams, inundation of large areas of productive land for source and terminal stor-

Figure 40.—Interstate Water Transfer Routes Assessed by the U.S. Army Corps of Engineers


Montana
North Dakota
South Dakota
Wyoming
Nebraska
Iowa
Colorado
Kansas
Missouri
New Mexico
Oklahoma
Arkansas
Texas
Louisiana
A
B
C
D
Missouri R. at Ft. Randall
Missouri R. at St. Joseph
Arkansas R. at Van Buren
White R. at Clarendon
Arkansas R. at Pine Bluff
Quachita R. at Camden
Sulphur R. at Darden
Sabine R. at Tatum
Red R. at fulton
Legend:
Alternative routes
Terminal reservoir sites
Source reservoirs
Ogallala aquifer

SOURCE: High Plains Associates, *Six-State High Plains Ogallala Aquifer Regional Resources Study* (summary, July 1982), p. 71, fig. VI-5. Original source: U.S. Army Corps of Engineers, "Water Transfer Elements of High Plains-Ogallala Aquifer Study" (review draft, January 1982), fig. 5.

age, conversion of large amounts of agricultural land to other uses, and disruption of wildlife migratory patterns.

Other considerations and possible limitations to interbasin transfer, though not identified by the High Plains study, include:

- treaty requirements and restrictions—e.g., the Mexican Water Treaty;
- commitments under the Wild and Scenic Rivers System;
- Federal and State statutory prohibitions against interbasin transfers, particularly interstate;
- vested rights to the waters of the source stream;
- allocations under interstate compacts;
- uncertainties concerning Federal reserved water rights and Indian water rights;
- lack of comprehensive, multipurpose, up-to-date regional planning encompassing both the source river basin and prospective affected area;
- lack of State water plans in many States;
- lack of generally accepted projections of future consumptive water demands in the source basins and receiving States; and,
- public opposition in the source basins to water transfer.

In the present and foreseeable future, political, financial, legal, and institutional considerations probably will preclude the use of extensive interbasin transfers of water to sustain irrigated agriculture in arid and semiarid regions of the West. Major changes in Federal and State laws and policies; provisions of large amounts of Federal and State funds; comprehensive, multipurpose, regional planning for water and other resources; and major changes in public perceptions and attitudes would be necessary before such transfers could be implemented. For example, the Colorado River Basin Project Act of 1968 (Public Law 90-537) prohibited planning by Federal agencies or with Federal funds for water diversions from the Columbia River Basin for use outside that basin. The initial 10-year moratorium has since been extended for another 10 years by the Reclamation Safety of Dams Act of 1978 (Public Law 95-578).

Technologies That Conserve Existing Water Supplies

Flexible Delivery Systems

INTRODUCTION

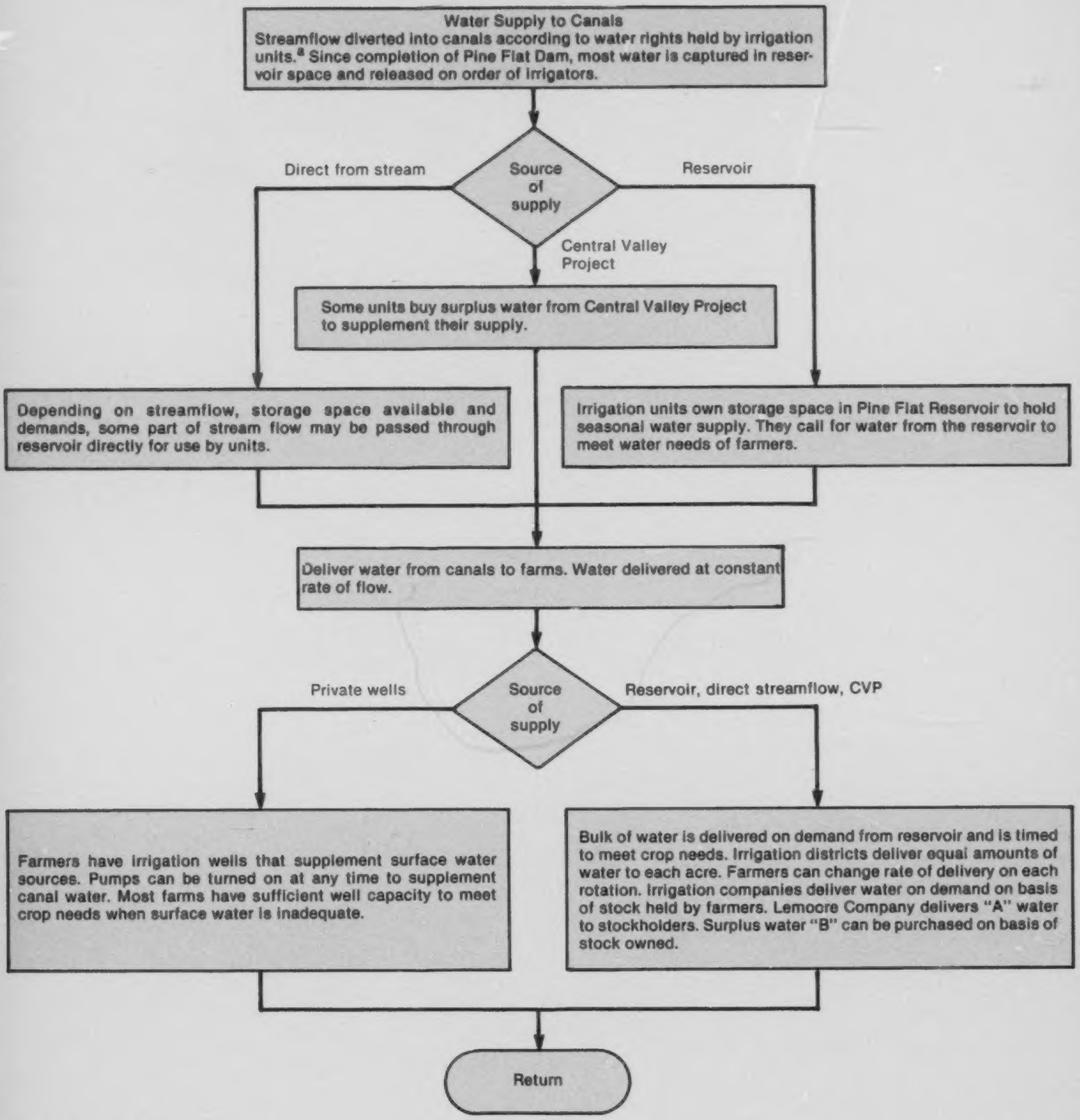
An adequate water supply is a critical aspect of surface water management. Timely water delivery is a second key element. Onfarm and off-farm irrigation systems that use surface water have two major features: a physical system of storage and conveyance and a managing organization to oversee distribution. Physical components generally include one or more storage reservoirs, diversion works to channel water into the conveyance system, a conveyance system with structures for flow control, and a distribution system that brings water to the individual user. Throughout the system, control gates or pumps regulate water levels and control the quantity of water being discharged through or into a particular structure.

The Federal Government builds and operates many reservoirs and major conveyance systems in the Western States, but many non-Federal public and private systems also exist. If Federal water is to be used for irrigation, it is sold to irrigation districts and/or canal companies. The exact arrangements for water distribution to individuals vary considerably from place to place. They include procedures that allot water based on crops, farm location, shares owned in the irrigation system, time of settlement, and other factors (fig. 41).

Operations of surface water systems are complex. Where sufficient supplies of water exist and conveyance systems are capable of transporting variable flows, a water system can be operated to meet all users' potential demands. However, in most arid and semiarid regions, systems that respond to unregulated demand are not feasible because water supply or system capacity is limited. Here, systems that are designed around supply have been more common.

The amount and timing of surface water flow in a supply-type system is controlled upstream. Federal or local project operators release water

Figure 41.—Irrigation Water Distribution Procedure, Kings River, Calif.



Water Supply to Canals
Streamflow diverted into canals according to water rights held by irrigation units.[a] Since completion of Pine Flat Dam, most water is captured in reservoir space and released on order of irrigators.

Some units buy surplus water from Central Valley Project to supplement their supply.

Depending on streamflow, storage space available and demands, some part of stream flow may be passed through reservoir directly for use by units.

Irrigation units own storage space in Pine Flat Reservoir to hold seasonal water supply. They call for water from the reservoir to meet water needs of farmers.

Deliver water from canals to farms. Water delivered at constant rate of flow.

Farmers have irrigation wells that supplement surface water sources. Pumps can be turned on at any time to supplement canal water. Most farms have sufficient well capacity to meet crop needs when surface water is inadequate.

Bulk of water is delivered on demand from reservoir and is timed to meet crop needs. Irrigation districts deliver equal amounts of water to each acre. Farmers can change rate of delivery on each rotation. Irrigation companies deliver water on demand on basis of stock held by farmers. Lemoore Company delivers "A" water to stockholders. Surplus water "B" can be purchased on basis of stock owned.

[a] Units are irrigation companies and districts.

SOURCE: Raymond L. Anderson and Arthur Maass, "A Simulation of Irrigation Systems," U.S. Department of Agriculture Technical Bulletin No. 1431, (Washington, D.C. 1978), p. 71.

from an upstream source based on "water orders" that anticipate downstream needs. The water then moves into a main canal (managed by Federal or local organizations), through a system of smaller canals, and is delivered to the farm. If farmers or districts decide not to use the water, it continues to move through the system and is spilled at the lower end of the canal.

Districts have formal rules and regulations for water distribution. Often, delivery schedules are developed in advance and are fixed for time and length. Adjustment in timing, duration, or quantity of water application is limited. For example, if several users are allowed to shut off water, flow along the entire canal system changes, and canal banks may overtop. While these rules allow close control of water in the system and enable officials to maintain accurate records of water deliveries, the amount and timing of water deliveries facilitate water distribution rather than accommodate crop needs. This situation limits the amount of water conservation that is possible. A variety of technologies for providing improved flexibility in water delivery are being examined.

Automated Upstream Control.—Stabilization of water levels in a conveyance system is difficult with conventional, manually operated check gates. In recent years, many irrigation districts have installed automated gates that maintain a constant water level regardless of

Box N.—Water Delivery: Pulling It Down and Putting Some Over the Hill

I suppose it was partly the memory of that [raft trip] that led me to visit, one summer morning in Sacramento, the Operations Control Center for the California State Water Project. Actually so much water is moved around California by so many different agencies that maybe only the movers themselves know on any given day whose water is where . . . . They collect this water up in the granite keeps of the Sierra Nevada and they store roughly a trillion gallons of it behind the Oroville Dam and every morning, down at the Project's headquarters in Sacramento, they decide how much of their water they want to move the next day. They make this morning decision according to supply and demand, which is simple in theory but rather more complicated in practice. In theory each of the Project's five field divisions . . . places a call to headquarters before 9 a.m. and tells the dispatchers how much water is needed by its local water contractors, who have in turn based their morning estimates on orders from growers and other big users. A schedule is made. The gates open and close according to schedule. The water flows south and the deliveries are made.

In practice, this requires prodigious coordination, precision, and the best efforts of several human minds and that of a Univac 418. In practice it might be necessary to hold large flows of water for power production, or to flush out encroaching salinity in the Sacramento-San Joaquin Delta, the most ecologically sensitive point on the system. In practice a sudden rain might obviate the need for a delivery when that delivery is already on its way. In practice what is being delivered here is an enormous volume of water, not quarts of milk or spools of thread, and it takes 2 days to move such a delivery down through Oroville into the Delta, which is the great pooling place for California water and has been for some years alive with electronic sensors and telemetering equipment and men blocking channels and diverting flows and shoveling fish away from the pumps. It takes perhaps another 6 days to move this same water down the Calfornia Aqueduct from the Delta to the Tehachapi and put it over the hill to Southern California. "Putting some over the hill" is what they say around the Project Operations Control Center when they want to indicate that they are pumping Aqueduct water from the floor of the San Joaquin Valley up and over the Tehachapi Mountains. "Pulling it down" is what they say when they want to indicate that they are lowering a water level somewhere in the system. They can put some over the hill by remote control from this room in Sacramento with its Univac and its big board and its flashing lights . . . [and] with its locked doors and its ringing alarms and its constant printouts of data from sensors out there in the water itself . . . . I stayed as long as I could and watched the system work on the big board with the lighted checkpoints. The Delta salinity report was coming in on one of the teletypes behind me. The Delta tidal report was coming in on another. The earthquake board, which has been desensitized to sound its alarm (a beeping tone for southern California, a high-pitched tone for the north) only for those earthquakes which register at least 3.0 on the Richter Scale, was silent. I had no further business in this room and yet I wanted to stay the day . . . .

SOURCE: Excerpted from: Joan Didion, "Holy Water," *The White Album* (New York: Simon & Schuster, Inc., 1979), 1977, pp. 60-62, 66.

water flow. These gates do not change the basic operation of the system. For example, if water demand increases upstream, downstream gates automatically close to maintain a constant water level and users on the downstream end may not receive enough water. Conversely, a decrease in upstream demand automatically opens downstream gates to allow extra flow to pass. However, if supply exceeds demand, water may spill at the lower end of the canal system.

Downstream Control Systems.—Downstream control of irrigation water ("demand delivery") is a second category of canal control. Downstream control compares to water delivery in municipal systems where water is available any time an individual turns on the tap and at any flow rate, up to the limits of the piping system or regulation. A downstream controlled system automatically responds to the opening and closing of farm gate turnouts. If an irrigator opens a turnout gate in these systems, a water wave is transmitted upstream to a gate, which in turn opens to release extra water. An opposite reaction occurs when the turnout is shut off.

Downstream control has been achieved in parts of irrigation projects in the United States, and complete systems have been constructed in Morocco and Tunisia. Two types of downstream control have been used. In one type, a series of level-top canals are connected by controls that respond to changes in downstream water levels. If water is discharged from the downstream end of a pool, for example, the water surface drops at that end and the resulting wave causes the upstream canal gate to open wider. A second, more rapid response, downstream control relies on multiple-sensing devices to take continuous readings throughout a canal system. Data are relayed to a computer in the central office and gates are adjusted on the upstream end.

Regulating Reservoirs Along Irrigation Canals.—An alternative to upstream or downstream control is to use one or more regulating reservoirs along the irrigation canal to buffer imprecise upstream deliveries and to allow a demand schedule to be implemented in a largely upstream-controlled system. Irrigation water can be stored until it is needed, and response time to irrigator demand can be shortened.

Combination Control.—It is not necessary to have downstream control structures throughout the canal system to deliver water to farm turnouts on a demand schedule. Upstream control structures on the upper one-half or two-thirds of a system and a regulating reservoir below this point can be an economical alternative. Demand scheduling can then be implemented on the lower end of the conveyance system.

Centralized Scheduling Services.—The U.S. Bureau of Reclamation has been experimenting with an extension of downstream control that predicts water requirements in individual fields based on weather and crop data. Water requirements for the aggregate system can then be predicted and the complete operation can be prescheduled.

Onfarm Reservoirs.—Where irrigation districts deliver water on a fixed schedule, farmers may build onfarm reservoirs at the turnout point to store water until it is needed.

ASSESSMENT

Flexible delivery schedules are relatively new in concept, design, and implementation. For example, level-top and newer rapid-response downstream control methods remain experimental, design refinements are still required, and as yet, capital and labor costs remain high (31).

The main advantage of these delivery schedules is the choice they provide in duration, frequency, and quantity of water delivered to ensure that the crop receives water when needed but not in excess of the amount required. For example, automated upstream control provides irrigators with limited flexibility in operation of turnout flows (discharge openings). Downstream control allows an irrigator to have water when it is needed and simplifies canal company operations, since farmers determine delivery schedules. Combined methods of control have advantages of several control methods and generally reduce the risk of spillage and under-irrigation (4).

Advocates of these control methods note many benefits for individual irrigators. These include: higher crop production per unit of water applied; higher crop production per acre; less surface runoff, erosion, and sedimentation; less deep percolation and attendant loss of fertilizers and pesticides; less seepage; less ground water use; and reduced pumping requirements. With better control, any excess water may remain in the system with the result that instream flow may increase. Because less polluted water is returned to the stream, water quality may improve and deposition of suspended sediment in reservoirs and streams may decrease (20,40).

Delivery arrangements based on considerations of technical efficiency alone may not be easy to implement. Some factors that restrict implementation include (24):

Economomic limitations: Some irrigation systems are old and rehabilitation to achieve more flexibility is prohibitively expensive. Others, such as onfarm reservoirs, are expensive to build and maintain and take land out of crop production.

Training and education needs of engineers, managers, and designers: The expertise required for some onfarm measurements of soil moisture or water application, for example, may be beyond that which most irrigators have or want. Some irrigation districts do not have the capability for automated water forecasting and management.

Institutional considerations: Water rights doctrines in the Western States are based primarily on the appropriation doctrine with a water right tied to specific lands. Many decreed rights may be far in excess of irrigation requirements, using current or improved technology, but irrigators who use less water on their farms and ranches may not get the economic benefit of that water, since it becomes available to the next junior user. For example, farmers and ranchers may have little incentive to use downstream controls that could reduce the amount of water applied to fields unless economic losses—e.g., those from fertilizer leaching—can be demonstrated.

Accuracy of water measurement in canals and soil is an important requirement in flexible delivery systems. For instance, extensive field measurements are needed to calibrate the computer programs that predict crop water requirements for centralized scheduling services. Downstream control systems must be monitored to ensure that requests do not exceed the capacity of the system. Modern electronic measurement devices are available for accurate accounting of water in all parts of the system, but ensuring that farmers and managers have access to this equipment and to backup information is difficult.

Responsibility for maintaining water records is shifting in some areas. For example, Federal efforts in providing centralized scheduling services have been criticized as understaffed and unresponsive to individual requirements. Private agricultural consultants in some areas are replacing Bureau of Reclamation irrigation scheduling services, but this transition is not without friction (23).

Seepage Control

INTRODUCTION

Seepage occurs through the sides and bottoms of reservoirs and canals. Its extent depends largely on geology, soils, and topography. Many technologies used to make soils impervious for water harvesting (ch. VI) also can be used for seepage control. These include: 1) compacted earth, 2) rigid surfaces, 3) buried and exposed membranes, and 4) soil sealants. Each area must be evaluated individually before a control method is chosen. Soil characteristics, operating capacity and flow velocity of the irrigation canals, structural stability required, water quality, and safety and maintenance needs must all be analyzed.

Assessment

Water "losses" from seepage can be large enough in some areas to prevent reservoirs from filling (4). However, estimates of the problem's magnitude vary widely and are difficult to make. For example, Morrison and Johns (25)

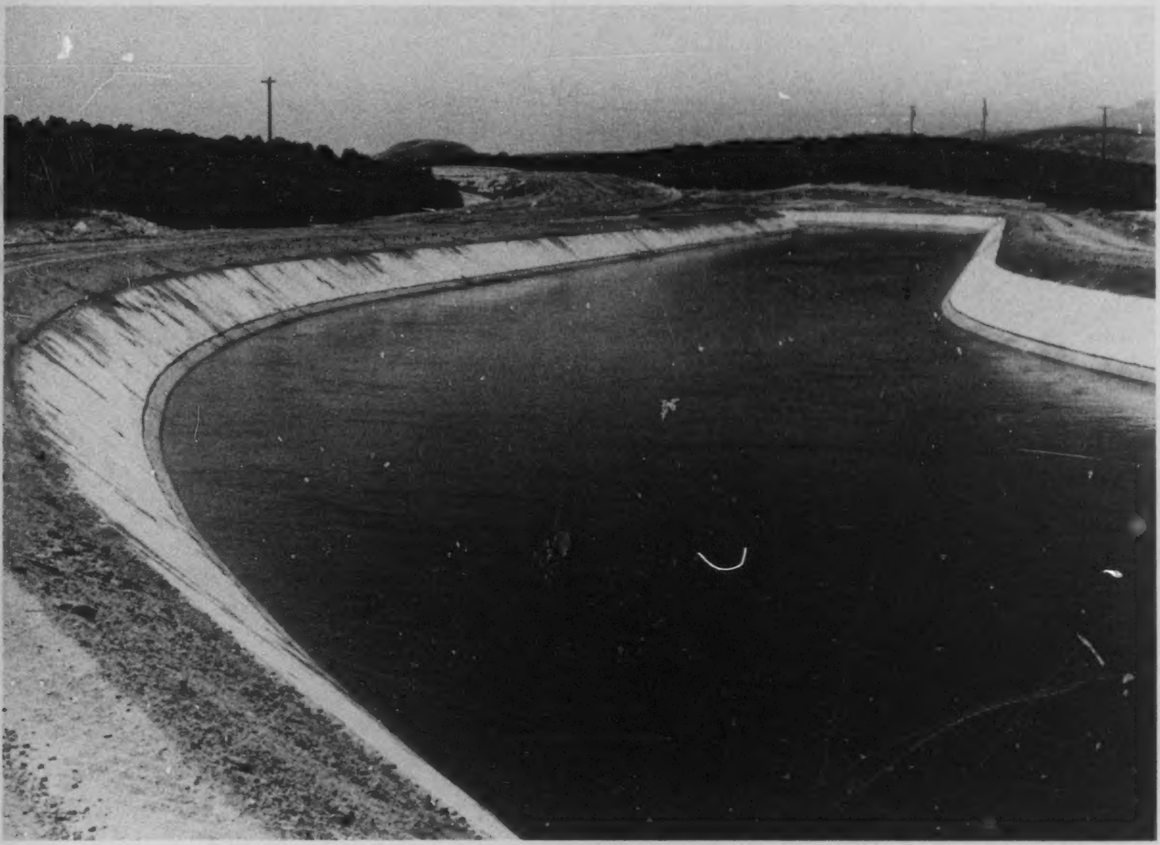


Photo credit: DOI-Bureau of Reclamation

This canal is lined to prevent seepage. It is part of the Central Valley Project Friant-Kern Canal stretching 150 miles from Fresno to Bakersfield, Calif.

suggest that eliminating seepage from irrigation systems could affect 1.5 million acre-ft of water. According to another author, consumption and conveyance water losses, including seepage and water use by riparian vegetation, account for about 5 percent of usable reservoir storage in the West (4). An earlier compilation of data by the Bureau of Reclamation showed that losses were considerably higher for many rivers (table 47).

Seepage control only "saves" water on a local basis, though, and its effects vary widely in different locations. Water lost to seepage is not lost to downstream users, to organisms in artificial or natural wetlands and streams, nor to the hydrologic system. For example, seepage from leaky irrigation systems in some areas provides ground water recharge. Depending on conditions, uncontrolled seepage may also result in soil salinization, waterlogging, or erosion of neighboring soils.

Seepage control currently is easier and less expensive than evaporation control (26). Both processes are expensive, however, and high cost is the primary limitation to use. As the relationship between standing water from inefficient irrigation and wildlife populations is explored, other limitations may be identified. In California, for example, applications of irrigation water in excess of plant needs and seepage from canals have contributed to increases in waterfowl populations. As water

Table 47.—Major Seepage Losses From Western Rivers, 1975

Basin	Acre-ft of annual seepage	Percent of total water diverted
Missouri River:		
Buford, Trenton, ND	6,149	35
Mirage Flats, NE	6,821	46
Buffalo Rapids, MT	42,478	55
Lower Yellowstone, MT, NE	57,985	21
North Platte, WY, NE	542,380	43
Milk River, MT	151,967	59
Columbia River:		
Crescent Lake, OR	32,830	49
Arnold, OR	8,590	38
Missoula Valley, MT	710	24
Umatilla, OR	60,335	30
Minidoka Palisades, ID, WY	1,457,949	24
Boise, ID, OR	784,655	35
Columbia, Basin, WA	676,320	23
Yakima, WA	520,832	24
Sacramento River:		
Orlando, CA	45,066	37
Colorado River:		
Salt River, AZ	526,177	39
Grand Valley, CO	59,661	18
Rio Grande River:		
Rio Grande, NM, TX	273,301	39
Middle Rio Grande, NM	121,360	24
Klamath River:		
Klamath, CA, OR	265,473	28
Total	5,641,039	

SOURCE: U.S. General Accounting Office, "More and Better Uses Could be Made of Billions of Gallons of Water by Improving Irrigation Delivery Systems," (Washington, D.C.: GAO-77-117, Sept. 2, 1977), p. 15. Original source: U.S. Bureau of Reclamation Annual Report, 1975.

conservation becomes more common, waterfowl are decreasing (35). It is not yet clear how these tradeoffs will be judged and managed (table 48).

Of the various types of seepage control, compacted earth linings often are available locally and at low cost. But these linings require specific soil conditions; when these conditions are not present, treated canals may continue to leak.

Rigid surface linings—e.g., concrete, asphalt, and soil-cement—are chosen when structural stability is important, such as when soils are unstable or near municipal areas. Concrete is most resistant to erosion, which is important when canals carry water at high velocities. Concrete-lined structures are susceptible to frost and chemical damage, though, and preventive features increase costs. Concrete linings may be either poured or applied under pneumatic pressure ("shotcrete"). The latter is limited to small canals and mild climates.

Asphalt and asphalt concrete also are effective linings. Asphalt concrete is durable, watertight, and erosion-resistant but requires careful compaction by large machinery. Therefore, it is used only in those large reservoirs and canals where cost is not prohibitive. Asphalt blown onto soil, then covered with more soil to prevent mechanical damage, is suitable for smaller structures and is less costly, but also less durable. Asphalt may also be mixed with other materials, such as rubber or fiberglass.

A rigid surface lining can also be made of a water, soil, and cement mixture. This mixture, called soil-cement, has high durability and low permeability if mixed and applied properly. It can be made only with relatively fine-grained soils and requires careful compaction (6).

Many different types of membranes have been used to line canals, sometimes only experimentally. These include synthetic rubber, prefabricated asphalt sheets, fiberglass-reinforced polyester, and other types of plastics. Thin membranes placed on the inside surface of a canal are exposed to weathering, vandalism, erosion, animals, and weeds. Such liners require careful ditch preparation to remove sharp objects and to ensure that the liners lie flat. Asphalt or plastic liners are usually covered by about a foot of earth. Asphalt linings have been in place for over 20 years; plastic linings have been used for almost 30 years, but detailed analysis of their performance covers a shorter period of time. Both are relatively low cost and effective. Rubber has been used less because it costs about three times as much as plastic (25).

A wide variety of soil sealants has also been used to eliminate canal and reservoir seepage. These agents may physically plug soil pores, form a distinct impermeable membrane, or chemically react with soil constituents. Soil sealants must be nontoxic to humans, animals, and crops; withstand a broad range of water quality; and resist breakdown by animals, equipment, erosion, and water pressure. Var-

Table 48.—Tradeoffs Between Agricultural and Wildlife Practices: California's Sacramento Basin

Practice	Opportunity for water saving	Agricultural viewpoint		Fish-wildlife-recreation viewpoint		Comments
		Positive	Negative	Positive	Negative	
Increase ground water pumpage	Possibly very large	Farmers gain operating independence and dry-year flexibility	High initial cost; big energy user	Reduces diversions from river	May increase percolation	One of two true means of saving water in basins
Increase reservoir storage	Moderately large	Increased dry-year supply	None	Decreases peak flows; increases dry-year summer flows; enhances reservoir-type fisheries	Would flood out native lands	Opportunity for true in-basin water savings
Reduce water applied to rice	Large, possible several hundred thousand acre-feet	Should produce a large net saving in applied water use; save energy and fertility	Would increase irrigation management costs; increase TDS of drainage water	Would tend to reduce diversions from the Sacramento River, leaving more water for in-channel use	Would decrease drain flows, hence diminish riparian vegetation and fish flows, increase TDS and water temperatures	No savings would result unless storage provided
Level all rice paddies, form rectangles	Included above	Would decrease applied water use by an estimated 5%; increase yield, reduce water management and harvest costs, increase net profit	Would take land out of production for one crop year; require capital outlay	Included above	Elimination of berms would reduce wildlife habitat	Now catching on rapidly in rice-growing areas
Drain wet mountain meadows; improve water management	Small	Would reduce water use; increase forage production	Would require annual maintenance cost; high original investment	None	Would reduce wetland habitat reduce late summer downstream flows	As time goes on, practice will be employed through the incentive to increase forage production
District practices; canal lining (reduce seepage); increased use of relift pumps, control ditch bank vegetation, clear channels	Large, could reduce district demands	These practices will decrease water demands on a district basis; could increase yields and decrease fertilizer needs	Would require more energy, capital, and manpower, increase the unit cost of water, leave drain water users with no available supply	None	Would reduce wetland habitat, reduce fish flows, raise water temperatures, increase TDS, concentrate pesticides, and increase channel velocities in some areas	Must develop incentives for districts to take action; must persuade people that water-saving practices are necessary

SOURCE: State of California, *Water Conservation in California*, Department of Water Resources Bulletin No. 198 (Sacramento, Calif.: May 1976), p. 70.

ious sodium salts meet these conditions and a sodium-treated reservoir will have a lifespan of many years (11). Soil sealants of other types, such as bentonite clays, have given variable results with differing soil types.

Evaporation Control

INTRODUCTION

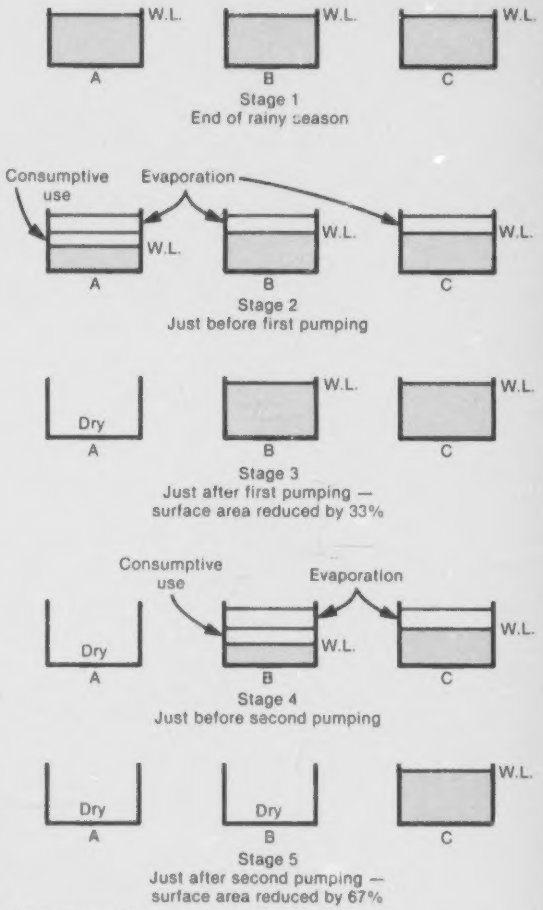
The process of evaporation requires a source of energy to vaporize water and a mechanism to transfer water vapor from the liquid's surface to the air. The climate in arid and semiarid lands provides both factors in abundance, and evaporation is high. Solar energy drives evaporation while low atmospheric humidity and frequent high winds accelerate the transfer of water vapor into the air.

Since conserving collected water is one of the most economical methods of maintaining an adequate water supply, a great deal of research has sought effective evaporation control technologies. These technologies increase water supplies, in effect, by increasing reservoir capacity without new construction. They alter the processes that contribute to evaporation by: 1) lessening the amount of energy that reaches the water surface to drive evaporation, and 2) altering the ease with which vaporized water moves into the air.

Four methods of controlling evaporation have received attention: 1) surface-area reduction, 2) reflective coatings, 3) surface films, and 4) mechanical covers. Surface-area reduction can be achieved by selecting proper sites, by diking to eliminate shallow areas of each reservoir, by deepening existing reservoirs, or by compartmentalizing them. Deepening reservoirs reduces evaporation both by exposing less water surface to warm, dry air and by lowering the temperature of the deeper water (and thus increasing the amount of energy needed to evaporate that water). "Compartmented" reservoirs actually consist of several separate reservoirs of varying depths (fig. 42). Water is used from the shallower reservoir until the remaining water equals the storage capacity of the other compartments. Water from the first container is pumped to fill the others at that time. This process is repeated as other reservoirs are drawn down. It ensures that most reservoirs will have the lowest possible ratio of surface to volume water and thus the lowest evaporation.

Figure 42.—A Compartmented Reservoir in Operation

Water is used from and pumped between separate reservoirs so that the evaporative surface is as small as possible.


W.L.
W.L.
W.L.
A
B
C
Stage 1
End of rainy season
Consumptive use
Evaporation
W.L.
W.L.
W.L.
A
B
C
Stage 2
Just before first pumping
Dry
W.L.
W.L.
A
B
C
Stage 3
Just after first pumping — surface area reduced by 33%
Consumptive use
Evaporation
Dry
W.L.
W.L.
A
B
C
Stage 4
Just before second pumping
Dry
Dry
W.L.
A
B
C
Stage 5
Just after second pumping — surface area reduced by 67%

W.L. = water level

SOURCE: C. Brent Cluff, "Surface Storage for Water-Harvesting Agrisystems," *Rainfall Collection for Agriculture in Arid and Semiarid Regions*, G. R. Dutt, C. F. Hutchinson, and M. Anaya Garduno (eds.) (Slough, U.K.: Commonwealth Agricultural Bureaux, 1981), p. 27, fig. 1.

Reflective coatings are designed to reduce the amount of incident solar radiation reaching the water. They also may provide a barrier to vapor. Surface films, which do act as barriers, received considerable attention during the 1950's and 1960's. Single-molecule films of long-chain alcohols were applied, sometimes by airplane. More substantial floating covers also have been developed. These mechanical covers include polystyrene sheets, lightweight concrete slabs, wax blocks, and rubber sheets.

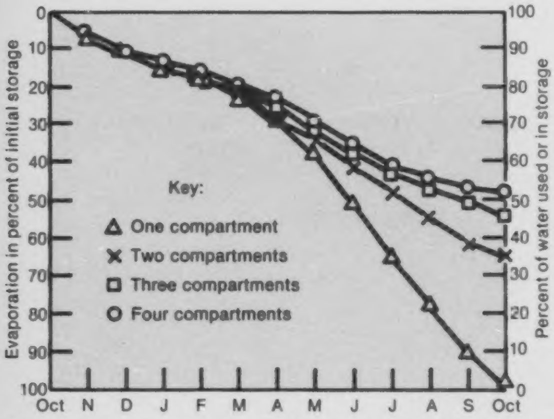
Assessment

Average evaporation from reservoirs throughout the West is approximately 6 percent. In some regions, though, reservoir evaporation may reach about 40 percent of usable storage (4). Small reservoirs, stock tanks, and farm ponds with large surface areas exposed to arid conditions may lose more water to evaporation than is used productively (26). Compartmented reservoirs can reduce evaporation substantially (fig. 43). Measurements made under idealized conditions in Arizona suggest that savings of 35 to 50 percent are possible, but these amounts vary in different climates (6).

Evaporation reductions achieved using different methods have been variable and often disappointing. For example, reflective coatings have reduced evaporation by about 50 percent for 1 month, but the materials used, such as perlite, eventually become waterlogged. Once coatings are wetted, evaporation savings drop to about 10 percent, making such technology impractical. Reflective coatings and surface films are unstable if the water surface is not still. Long-term field studies show that monomolecular layers of alcohols reduce evaporation only about 10 to 20 percent (4,14). These controls are most economical for large reservoirs or in highly regulated river systems where evaporation losses are large and increasing salinity levels must be controlled.

Figure 43.—Evaporation From Compartmented Reservoirs

Reservoirs with several compartments have the potential for reducing evaporation. The amount of water "saved" can be substantial, as illustrated in this idealized graph for Tucson, Ariz.



SOURCE: C. Brent Cluff, "Surface Water Storage for Water-Harvesting Agrisystems," *Rainfall Collection for Agriculture in Arid and Semiarid Regions*, G. R. Dutt, C. F. Hutchinson, and M. Anaya Garduno (eds.) (Slough, U.K.: Commonwealth Agricultural Bureaux, 1981), p. 28, fig. 2.

Mechanical covers are often simple and cost-effective and have the highest potential for use on small reservoirs, stock tanks, and ponds. Materials of various kinds have achieved reductions in evaporation of 80 to 90 percent. Only minor problems have been reported, such as damage by birds and weathering (14). Some elaborate types of covers are specially treated to retard weathering, but this makes them too expensive to use for conventional agriculture. They may be cost-effective when used in conjunction with water-harvesting methods, compartmented reservoirs, or less-than-full irrigation.

Vegetation Management In and Near Surface Water

Riparian Vegetation

INTRODUCTION

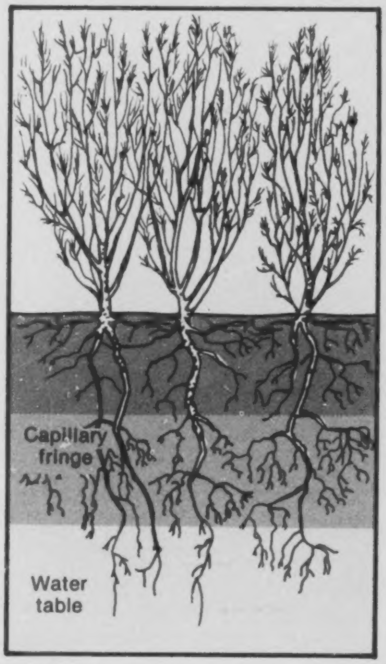
Riparian zones constitute only a small fraction of Western lands. Their scarcity belies their critical role, however, in affecting and maintaining watershed stability, water quality, livestock grazing, wildlife habitat, and recreation (22). These areas also are significant for agriculture; they provide high-quality forage and drinking water for livestock and can decrease soil erosion when in good condition. They may, however, use water intended for irrigated crops. Riparian zones also constitute an important esthetic and wildlife resource (table 49). For example, although riparian zones

Table 49.—Southwestern Birds That Rely on Wetland and Riparian Habitats

	Distribution of bird species among habitats (percent)			
Location (no. species)	Wetlands and/or only riparian	Riparian preferred	Nonriparian	Suburban and agricultural
Blue Point Cottonwoods (58)	45	29	24	2
Salt River Valley (86)	44	23	27	6
Central Arizona Mountains (102)	7	22	68	3
Flagstaff (125)	18	18	62	2
Grand Canyon (122)	16	14	68	2
Arizona (242)	30	22	46	2
Southwest Lowlands (166)	47	26	23	4

SOURCE: Adapted from R. Roy Johnson, "The Lower Colorado River," *Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems*, U.S. Department of Agriculture Forest Service General Technical Report WO-12 (Washington, D.C.: U.S. Government Printing Office, 1979), p. 43, table 2.

Figure 44.—Some Riparian Plants, Called Phreatophytes, Tap Ground Water



SOURCE: T. W. Robinson, *Phreatophytes*. U.S. Geological Survey Water-Supply Paper 1423 (Washington, D.C.: U.S. Government Printing Office, 1958), p. 10.

represent less than 1 percent of public arid lands, 75 percent of all sagebrush steppe wildlife in southwest Wyoming depends on these areas (33,34), and over half of the land designated Arizona State Natural Areas include riparian areas (3).

Riparian zones are identified by characteristic shrubs, trees, and grasses that are associated with abundant water. Plants that tap ground water, called "phreatophytes," are common (fig. 44 and table 50). Plant species vary throughout the West as a result of climatic and management differences. The present vegetation sometimes is dominated by exotic species, such as saltcedar, which have invaded wide geographic areas and replaced native cottonwoods, willows, and mesquite.

Assessment

Knowledge of the hydrologic role of riparian vegetation has changed considerably in the past 30 years. Therefore, the approach to management also has changed. Early work indicated that phreatophytes "waste tremendous quantities of ground water each year," cover about 16 million acres in the 17 Western States, and use as much as 25 million acre-ft of water annually (32). Such estimates often were based on limited studies, however, and extrapolation to the entire West is suspect.

Early workers assumed that most, if not all, of the water "saved" by removing riparian vegetation would remain in ground or surface waters and be available for direct human use. While some streamside plants use large amounts of water, removing the plants does not necessarily make this water available for other uses. One of the first long-term measures of water availability before and after clearing was completed in 1982. These Arizona results indicate that water "savings" depend on the vegetation that replaces phreatophytes. Annual average water "losses" are likely to increase by 60 percent, remain about the same, or decrease by 2 percent if three different irrigated

Table 50.—Widespread Phreatophytes of the Western United States

Common name	Scientific name
Baccharis	*Baccharis* spp.
Rabbitbrush	*Chrysothamnus* spp.
Saltgrass	*Distichlis* spp.
Wildrye	*Elymus* spp.
Velvet ash	*Fraxinus velutina* Torrey
Wirerush	*Juncus balticus* Willdenow
Sprangletop	*Leptochloa fascicularis* (Lamarck) A. Gray
Alfalfa	*Medicago sativa* Linnaeus
Reed	*Phragmites communis* Trinius
Engelmann spruce	*Picea engelmanni* Parry
Cottonwood, quaking aspen	*Populus* spp.
Mesquite	*Prosopis* spp.
Willow	*Salix* spp.
Elderberry	*Sambucus* spp.
Big greasewood	*Sarcobatus vermiculatus* (Hook) Torrey
Buffalo berry	*Shepherdia* spp.
Alkali sacaton	*Sporobolus airoides* Torry
Saltwort	*Sueda depressa* Watson
Saltcedar	*Tamarix* spp.

SOURCE: T. W. Robinson, *Phreatophytes*, U.S. Geological Survey Water-Supply Paper 1423 (Washington, D.C.: U.S. Government Printing Office, 1958), pp. 32-40, table 1, in part.

forage grasses are substituted for saltcedar and mesquite. Without irrigation, more water probably would remain in ground and surface supplies, but no data verifies this (9).

Vegetation along rivers and canals also traps sediments, with both positive and negative results. In areas such as the Pacific Northwest, where soil erosion is severe, streamside plantings of phreatophytes and other plants supplement older structural control methods. In other areas, sediment is trapped upstream of reservoirs, extending their useful life. However, dense growth of phreatophytes can also block channels (fig. 45). When water flow is constricted, flooding can increase.

There is less emphasis placed on eradication of phreatophytes now that the results of past attempts appear questionable and multiple-use management is more common. In fact, phreatophytes such as mesquite and rubber rabbitbrush are potential new crops in the West (ch. IX). If they are developed, what is now considered to be a waste of agricultural water could become a beneficial use.

The technologies used to manage riparian vegetation are similar to those for brush management (chs. VI and IX) but are often constrained by the need to prevent water pollution. Chemical control and the use of fire are limited, and riparian vegetation is often mechanically cleared as a result. Dropping ground water levels quickly may be a practical method of control if a simultaneous use of the water ensures that the water table remains below plant roots. Antitranspirants, nondestructive chemical methods used to slow water use, have been applied to riparian vegetation. They are costly, their application is difficult, and their long-term effects on wildlife are unknown (10).

Aquatic Plants

INTRODUCTION

A number of organisms that live in and near water can affect water conveyances. Beaver and muskrat dams may block channels, and invertebrates may clog closed irrigation pipes, but aquatic plants present the greatest problems for irrigators (table 51). Such plants interfere with water movement both mechanically and biologically by slowing the movement of irrigation water, disrupting control devices, and causing leaks in canal linings. Some may lose water to the atmosphere at rates greater than an open water surface (16).

Technologies for controlling and managing aquatic plants include preventive, mechanical, biological, and chemical methods. Preventive measures are often overlooked. These include:

- encouraging growth of adapted plants compatible with irrigation,
- decreasing sources of seeds and other propagules,
- decreasing supplies of potential plant nutrients, and
- designing an irrigation system for quick establishment of cover plants.

Mechanical controls were common before the availability of pesticides. Weeds were hand cut, raked, dredged, or chained. Biological control methods are newer; these include the use of herbivorous fish, competitive plants, and in-

Box O.—Of Beavers and Willows: Restoring Riparin Habitats in Wyoming

Some riparian habitats have suffered from mismanagement. In southwestern Wyoming, for example, about 83 percent of these communities have been lost. This resulted in decreased forage, accelerated streambank erosion, lower water quality, declining water tables, and loss of fisheries habitat.

The Rock Springs District of the Bureau of Land Management is one of the groups attempting to reverse these conditions. Healthy willows appear to be key to this process. Some riparian areas have been restored, with the cooperation of ranchers, by 1 to 3 years' rest from grazing. Forage production increased by almost 2,000 pounds per acre in one study site where grazing management was tailored to willows.

In other areas, stream conditions require that more complex technology be used. Costs for improving these areas have ranged from $3,000 to $100,000 per site when structural methods were applied. A newer approach provides building materials at low cost to a different kind of engineer: beavers. As beavers use wood and old tires to build new dams, water storage increases and streams stabilize. This sets the stage for riparian recovery as willows and other plants colonize flooded areas.

Private companies also have undertaken projects to restore riparian habitats. Timberline Reclamations, Inc., for example, has provided consulting services throughout the Western States, applying both engineering and biological approaches to natural resources. According to the company, the effects sometimes have been large: restoration of a creek in Montana which had been destroyed by grazing resulted in a substantial increase in property values based solely on the improved fishery.

These technologies appear to be very effective. They are too new, however, to have long-term records.

SOURCE: Excerpted from: Bruce H. Smith, "Riparian Willow Management: Its Problems and Potentials Within the Scope of Multiple Use on Public Lands" (Lander, Wyo.: University of Wyoming, Shrub Ecology Workshop, June 5-6, 1980) and "Restoration of Riparian Habitats Within the BLM-Rock Springs District" (Salt Lake City, Utah: Native Plants, Inc., Wildlife Habitat Rehabilitation and Reclamation Symposium, Jan. 10-11, 1983). Timberline Reclamation, Inc., Bozeman, Mont., n.d.

sects and pathogens. Chemical methods include both water and ditchbank applications of pesticides.

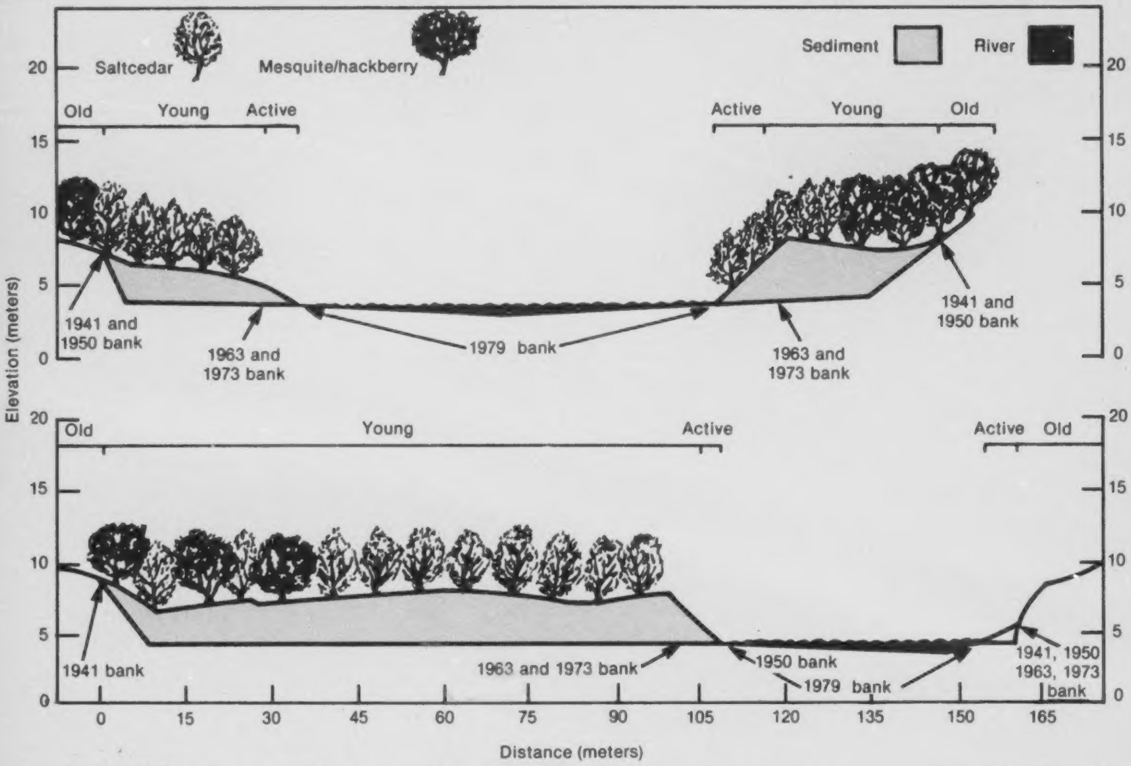
ASSESSMENT

Recent estimates indicate that aquatic plants interfere with irrigation in as many as 60 percent of all canals in the Western United States. As many as 85,000 miles of canals could be adversely affected. Some water managers believe that aquatic weed problems are becoming more severe. Both the introduction and spread of prolific, nonnative plants and the rapid eutrophication, or nutrient buildup, of surface waters contribute to these changes. These problems have a large economic impact. For example, the Bureau of Reclamation spent about $6 million annually to control aquatic plants in its water systems in the late 1970's (36).

Perhaps the most effective and least costly approach to aquatic-plant management is prevention. But if part of the prevention system breaks down, other methods are necessary.

There has been a resurgence of interest in mechanical methods as stringent restrictions on herbicides take effect and aquatic plants are recognized as a renewable resource (27). Mechanical control is especially important when: 1) herbicide residues cannot be tolerated, 2) water conditions preclude isolation of chemicals, 3) nutrient removal is important, 4) large-scale biomass removal is required before beginning an integrated-management program, or 5) biomass has economic value. Mechanical methods tend to be expensive, time-consuming, and laborious. If the plants are not removed, they can clog downstream structures. Mechanical systems are used by several municipalities,

Figure 45.—Cross Section of Brazos River, Tex., Before and After Saltcedar Invasion


Saltcedar
Mesquite/hackberry
Sediment
River
Old
Young
Active
Active
Young
Old
1941 and 1950 bank
1963 and 1973 bank
1979 bank
1963 and 1973 bank
1941 and 1950 bank
Old
Young
Active
Active
Old
1941 bank
1963 and 1973 bank
1950 bank
1979 bank
1941, 1950 1963, 1973 bank
Elevation (meters)
0
5
10
15
20
Distance (meters)
0
15
30
45
60
75
90
105
120
135
150
165

SOURCE: W. H. Blackburn, R. W. Knight, and J. L. Schuster, "Saltcedar Influence on Sedimentation in the Brazos River," *Journal of Soil and Water Conservation* 37(5):301, September/October 1982, fig. 3.

Table 51.—Major Aquatic Weeds and Extent of Total U.S. Infestation

Plants (common/scientific names)	Present extent of infestation (acres)	Potential infestation area (acres)
Waterhyacinth *Eichornia crassipes* (Mart.) Solms	1,000,000	9,550,000
Watermilfoil *Myriophyllum* spp.	500,000	17,450,000
Alligatorweed Alternanthera philoxeroides (Mart.) Griseb.	60,000	9,850,000
Hydrilla *Hydrilla verticillata* (L. f.) Royle	50,000	4,305,000
Egeria *Egeria densa* (Planch.)	50,000	10,845,000
Waterlettuce *Pistia stratiotes* L.	3,000	9,550,000
Waterchestnut Trapa natans L.	3,000	1,050,000
Total	1,666,000	62,600,000

SOURCES: U.S. Department of Agriculture, "Report of the S.E.A. Research Planning Conference on Aquatic Weed Control" (Davis, C. Sept. 13-15, 1977), 1978, p. 50. Edward E. Terrell, *A Checklist of Names for 3,000 Vascular Plants of Economic Importance*, Agriculture Handbook No. 505 (Washington, D.C.: U.S. Government Printing Office, May 1977).

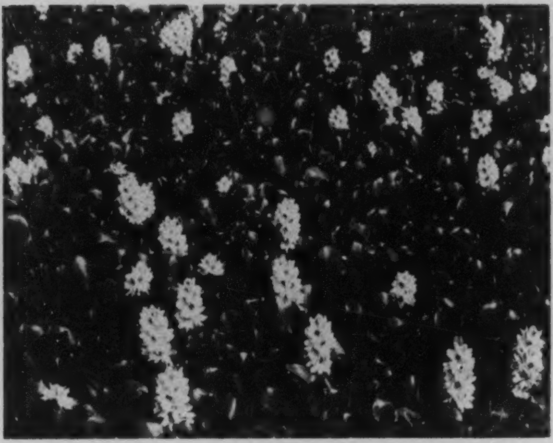


Photo credit: USDA-Soil Conservation Service

Waterhyacinths are important aquatic weeds in California, other warm parts of the United States, and many of the world's reservoirs and rivers

counties, lake owners' associations, State and Federal agencies, and private contractors. Despite this history, no focused data base exists on the potential for marketing products from weeds (36). Research at a number of locations is evaluating harvesting equipment, plant processing, and the use of weeds for compost, biogas production, or animal feed.

Biological methods of pest control are generally effective, economical, and minimally detrimental to the environment. Insects are being used to control alligatorweed and there are several promising candidates for controlling waterhyacinth (21). The grass carp, a fish introduced from China, can control many types of aquatic plants, but fear persists that it could become a pest and eliminate native game fish (30). Different species of spikerush (*Eleocharis* spp.), native aquatic plants, are able to eliminate or reduce populations of aquatic weeds by a combination of competition for nutrients and space and chemical "interactions," or allelopathy (13).* Nonetheless, effective biological control, which is both widely available and acceptable for a large number of different species, is still rare.

Chemical control by herbicides is sometimes faster and easier than other methods. In some cases, chemicals can nearly eliminate aquatic plants and reduce problems of reinfestation. Some are selective enough to remove only those plants that are undesirable, providing a way to alter the habitat for specific purposes. But some chemical controls have serious drawbacks—e.g., high cost, toxicity to fish, lack of specificity, toxicity to crops and livestock—or other hazards. Recent restrictions on the use of chemicals, especially in and around water, has limited the chemical controls available (table 52). Other types of nonpesticidal chemicals such as plant growth regulators or dyes that darken water and shade plants are promising.

In the case of large bodies of water, single ownership is rare, and management for multiple uses makes chemical treatments of any kind difficult. Integrated weed management, which combines the best of all types of control technologies in a long-term management plan, is a promising approach under those and other conditions. However, many of the early mechanical and chemical control technologies were not intended for use in integrated weed management systems. Therefore, they are not well adapted for this purpose. New integrated-management schemes are only in early stages of development (29,36).

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*Allelopathy is the production of chemical substances by one species that inhibit the germination, growth, or life of another species.

Table 52.—Restrictions on the Use of Aquatic Herbicides

Aquatic weed	Herbicide	Rate	Restrictions
Algae (phytoplankton, filamentous, *Chara*)	Copper sulfate	2.7 lb/A-ft.	Do not use in trout waters
	Copper chelates (Cutrine Plus)[a]	0.6-1.2 gal/A-ft.	Do not use in trout waters
	Endothall (Hydrothol 191)[a]	1.1 pts/A-ft.	F = 3 days; L, D = 7 days Do not use for crop irrigation
	Simazine (Aquazine)	1-3.4 lb/A-ft.	I, L, D = 12 months
Submersed plants (coontail, watermilfoil, pondweeds such as sago, curlyleaf, leafy)	Endothall (Aquathol K)[a]	1.3 gal/A-ft.	S = 1 day; F = 3 days; 1[b], D = 7 days
	Diquat	1-2 gal/SA	S, L, I = 10 days;
	Simazine (Aquazine)	3.4-6.8 lb/A-ft.	I, L, D = 12 months
Free-floating plants (duckweed, watermeal)	Diquat	1 gal/SA	S, L, I = 10 days; D = 14 days
	Simazine (Aquazine)	3.4-6.8 lb/A-ft.	I, L, D = 12 months
Rooted-floating plants (waterlilies, spatterdock)	2, 4-D (Aquakleen)	200 lb/SA	Do not apply to waters for I, D, dairy animals
Emersed plants (cattails, perennial grasses)	Dalapon (Dowpon + wetting agent)	15 lb/SA	Restrict spray to plant foliage

KEY: F = fishing; I = irrigation; L = livestock; D = domestic use; SA = surface area; A-ft = acre-foot.

[a] These are liquid formulations which are also available as granules.

[b] Treated water may be used for sprinkling bent grass immediately.

SOURCE: Carole A. Lembi, "Aquatic Weed Control—In Review," *Weeds Today* 11(3):5, 1980, table 1.

CONCLUSIONS

Technologies to develop large sources of previously unavailable surface water are limited. For example, large-scale interbasin transfers are feasible technologically but constrained by economic, legal, social, and environmental considerations. Similarly, conversion of saltwater to freshwater is very expensive and likely to be limited to municipal and industrial uses. Neither large-scale interbasin transfers nor current methods of desalination are likely to provide water for agriculture in the near term.

Aging water storage and conveyance facilities require major public and private investments to repair deterioration. This need, combined with economic, physical, social, and environmental factors, makes construction of new, large-scale storage facilities unlikely. Smaller projects, including ones on farms and ranches, continue to be built, often with State and local government or private financing or cost-sharing.

The short-term "losses" of water from storage and conveyance facilities by untimely irrigation water delivery, seepage, evaporation, and interference by plants are large. While a number of technologies have been proposed to "save" this water, few are applied widely. Their application may involve tradeoffs and the effect on the entire hydrologic cycle is often unknown.

Technologies for improving the timing of irrigation water delivery generally are promising. A wide variety of methods is being evaluated, but institutional factors may be the biggest factor limiting their adoption. High costs and low effectiveness limit application of many seepage and evaporation control technologies, especially on large lakes and reservoirs. Similar methods are economical now for use on small reservoirs or stock ponds. Because the amount of water transpired by phreatophytes and other riparian vegetation and the availability for other uses are uncertain, former eradication measures often have been replaced by multiple-use management of streamside lands. In some areas, especially the Southwest, where exotic plants have rapidly spread, control remains necessary, but the effect on the overall water balance is not known. Effective methods are available for managing aquatic plants.

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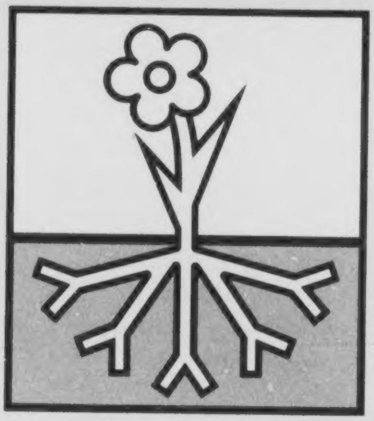

Technologies Affecting Soil Water

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Chapter VIII

Technologies Affecting Soil Water

Agricultural technologies that affect soil water have helped transform the "Great American Desert" into an area of high annual agricultural production. This change has occurred largely because of improved methods of conserving precipitation and the practice of irrigation. New technologies and changes in the amount and location of land to which they are applied continue to shape Western agriculture and evidence suggests that future changes will be as extensive as those of the past.

This chapter first discusses soil and water relationships, then examines some of the technologies that increase soil-water supplies. These technologies involve a gradient from conserved to added water. Some conserve precipitation, others supplement rainfall and snowfall with limited amounts of applied water, and another group provides enough additional water to fill the crop's requirements. "Irrigation" usually refers to the last type of technology, the one that uses the largest amount of applied water.

THE WATER SETTING: SOIL AND WATER RELATIONSHIPS

Additions of water to soil come from three sources: precipitation (snow, rain, sleet, or hail); application of irrigation water; and upward movement of water into the root zone from a water table (capillary rise). Losses from the soil occur through evaporation from the soil surface, transpiration by growing plants, and deep percolation (fig. 46). Soil plays a key role in the hydrologic cycle. Its properties help determine how much water runs off the land, the amount of water that can be supplied to growing plants, and the quantity of water that will percolate to the ground water.

Infiltration

Infiltration results from the interactions between soil, vegetation, landscape, and weather (e.g., rainfall intensity and duration), however, soil properties dominate the process. Coarse-textured soils ("texture" refers to the size of the soil particles), such as sands, or soils with good structure ("structure" refers to the arrangement of soil particles into aggregates) usually take in water quickly. Clay soils or those with a compacted surface layer take in water slowly (fig. 47). Another important determinant of infiltration is initial soil-water content. Generally, dry soils absorb water readily; water will move more slowly into a soil that is wet.

Site conditions also affect infiltration. Where slopes are steep, water moves rapidly across the surface with little time for infiltration. Conversely, water will move more slowly across nearly level areas and these sites generally experience less runoff.

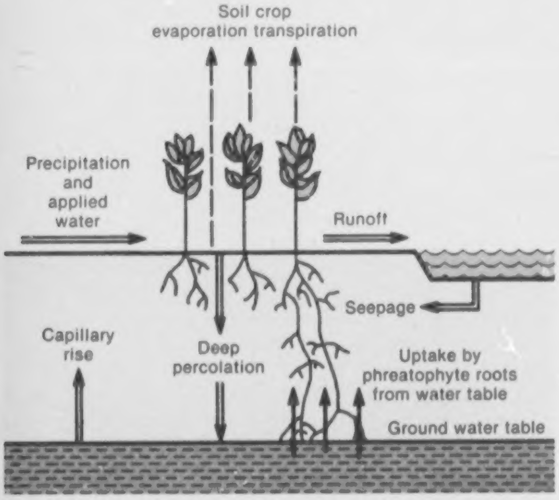
Vegetation can affect infiltration in several ways. Plants can intercept water before it reaches the soil surface and thereby reduce the amount of water available for infiltration. Vegetation can also facilitate water movement into soil by slowing its movement across the surface and allowing more time for infiltration and by protecting the soil surface from the impact of falling raindrops. Finally, plants and products of their decomposition can improve soil structure and thus infiltration.

Soil-Water Movement and Retention

Soil-water movement is a dynamic process. Soil water can move downward, upward, and laterally in response to different physical and biological conditions. During and after initial infiltration, for example, water generally moves

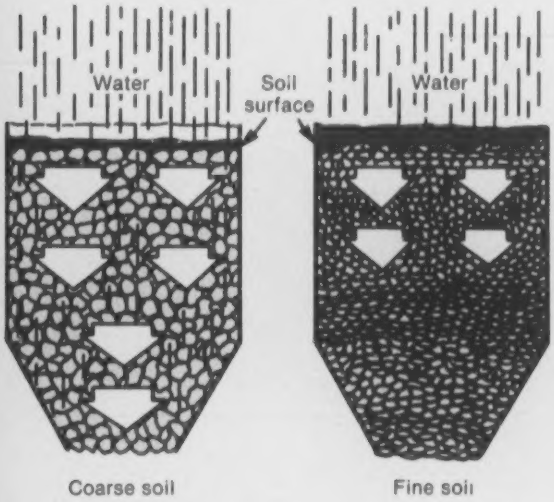
Figure 46.—The Role of Soil in the Hydrologic Cycle

Precipitation or applied water infiltrates the soil surface and is used by a growing plant or is lost through evaporation, percolation, or surface runoff. Some water is also added to the soil profile through capillary rise.


Soil crop
evaporation transpiration
Precipitation and applied water
Runoff
Seepage
Capillary rise
Deep percolation
Uptake by phreatophyte roots from water table
Ground water table

SOURCE: David C. Davenport and Robert M. Hagan, "Agricultural Water Conservation," *California Water Planning and Policy*, E. Engelbert (ed.), Water Resources Center, University of California at Davis, 1979.

Figure 47.—Soil Particle Size and Infiltration



Generally, the larger the soil particle and aggregate size, the faster the rate of water intake.

SOURCE: J. Howard Turner and Carl L. Anderson, *Planning for an Irrigation System* (Athens, Ga.: American Association for Vocational Instructional Materials, 1980).

downward and laterally in response to gravity and the "pull" of unwetted or drier soil particles. Water in excess of the soil's "storage capacity" will continue to move outward from the wetted soil.

Water also moves upward into the plant root zone by the process of capillary rise, which occurs where the water table is near the surface, or where fine-textured soils are present that can conduct water upward for considerable distances. Water movement is usually slow and except on some irrigated lands and in a few other areas, soil water derived from capillary rise does not account for a significant portion of soil-water supplies.

Soils differ in their ability to retain and redistribute moisture, and many of the factors that affect infiltration affect water retention and redistribution. These include: soil texture, soil structure, organic-matter content, clay type, depth of wetting and amount of water in the soil, the presence of impeding soil layers, and evapotranspiration. Generally, about one-half the water held in the soil after gravitational water (water that moves under the force of gravity and is not retained in the soil) has drained away can be used by plants. This quantity of water can be stored for a long period of time for later use by crops (table 53).

Soil-Water Losses

Water that could be used by plants can be "lost" in several ways. Losses can occur when water fails to infiltrate the soil and runs off the surface. After water is stored in the soil, evaporation, transpiration by plants of low economic value (e.g., weeds), and percolation beyond the plant root zone can reduce soil-water supplies. Evapotranspiration losses are especially critical in the arid and semiarid regions because water lost in this process cannot be recovered except through the course of the hydrologic cycle. Water lost in surface runoff and deep percolation generally remains a part of water supplies and can be recovered.

The amount of water lost in each process differs from site to site and changes over time,

Box P.—Soil Properties in the Arid and Semiarid Region

Soils are a product of climate, biological activity, topography, and mineral material acting together through time. These factors interact in varying degrees at a particular site and affect certain physical, chemical, and biological properties of soil. Some physical properties, such as texture and structure—i.e., the size of the soil particles and their arrangement into aggregates—are critical to soil-water relationships. Chemical properties such as nutrient status and acidity are important to plant growth. Biological properties—e.g., the presence of certain micro-organisms—are important in plant in animal decomposition and the recycling of plant nutrients.

Soil properties in the arid and semiarid region are dominated by climate, although its effect is modified by the other factors mentioned above. Low amounts of precipitation, for example, slow the rate of soil formation. Similarly, with low precipitation and sparse plant growth, soils that form on residual rock tend to be shallow. Plant root-restricting layers—e.g., caliche (a more or less cemented deposit of calcium carbonate)—may form because there is insufficient water to wash soluble minerals out of the soil.

Arid- and semiarid-climatic conditions are associated with other soil features. First, these soils are relatively fertile but often have high soluble salt levels that may restrict plant growth. Second, organic matter levels tend to be low because precipitation is not adequate for production of large amounts of vegetation. Consequently, soils often lack good structure. Recent research also suggests that soils with low organic matter do not support high microbial populations—e.g., fungi, bacteria, and algae—which are critical to decomposition of dead plants and animals and to nutrient recycling. Some essential plant nutrients—e.g., nitrogen and phosphorus—may be lacking because these elements are products of organic-matter decomposition. Finally, low levels of organic matter are associated with low nutrient-retention capacities.

Arid and semiarid soils are unique in other respects, particularly in their vulnerability to wind and water erosion, salinity, and compaction. More importantly, if these processes occur, the results are long lasting and not easily alleviated, given the slow rate of soil formation, low amounts of precipitation, and limited plant growth. The recently completed OTA assessment of the impacts of technology on the Nation's cropland and rangeland productivity (24) discusses these hazards in more detail.

Table 53.—Water Available to Plants per Foot of Soil for Various Soil Textures

Textural description	Available water (inches)
Coarse textured:	
Sands	0.4 -0.75
Loamy sands	0.75-1.25
Moderate coarse textures (sandy loams, fine loamy sands)	1.25-1.75
Medium textured (loams, silt loams)	1.50-2.30
Moderate fine textured (clay loam, silty or sandy clay loam)	1.75-2.0
Fine textured (sandy or silty clay, clay)	1.60-2.50

SOURCE: Hayden Ferguson, William Lyle, Charles Fenster, and Charles Wendt, *Dryland Agriculture*, OTA commissioned paper, August 1982.

depending on weather, soil, crop, and season of the year. Generally, these losses can be ordered as:

Transpiration > Evaporation > Runoff > Percolation.

As an example, where annual precipitation is scant, as in the arid Southwest, evaporation represents less than 10 percent of seasonal evapotranspiration (13). In other areas where rainfall is more abundant—e.g., the Great Plains—up to 50 percent of the precipitation may evaporate (11).

Agricultural practices can improve soil-water supplies in several ways. They can help to:

- increase the amount of water moving into the soil;
- increase the amount of water retained in the soil; and
- decrease the amount of water lost in surface runoff, evaporation, and deep percolation.

This chapter considers some of these technologies. Measures that affect plant transpiration are considered in chapter IX.*

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*For additional information on land and soil characteristics with agriculture see the OTA assessment, *Impacts of Technology on U.S. Cropland and Rangeland Productivity*, OTA-F-166, August 1982.

Box Q.—Soil-Water Measurement

A number of devices are used by researchers and farmers to measure soil-water conditions. These tools can help determine the amount of water available for plant growth. On irrigated fields, soil-water measurement can aid in determining water application schedules. It is important to note, however, that the ability of plants to remove water from soil is primarily related to the force with which water is held in the soil and not solely to soil-water content.

One of the oldest methods for measuring soil-water content is by gravimetric determination. In this process, soil samples are removed from desired depths and placed in cans to prevent moisture loss. The samples are weighed, heated to boil away the water, and weighed again. Water content is calculated as a percentage of dry weight and converted to a volume basis (e.g., inches per foot of soil) if bulk density of the soil is known (mass per unit volume of an oven-dried soil).

Using electrical-resistance gypsum blocks is a second means of estimating soil water. In this method, two electrodes are embedded in gypsum blocks and placed in the soil. An electrical current is passed through the electrodes and the resistance across the electrodes is measured. Resistance across the electrodes increases as the water content of the soil decreases. A calibration curve is used to determine the soil-water content.

A third device for measuring soil water is a tensiometer. Tensiometers measure the "force of attraction" of the soil for water and are calibrated to determine soil-water content in each soil. These tools vary in form. One type, a vacuum-gage tensiometer consists of a porous, fired clay cup which is attached to a vacuum gage by a water-filled pipe. If the cup is buried in dry soil—i.e., where the water has less energy than the water in the cup water will move from the cup into the soil. When the system comes to equilibrium, the vacuum gage measures the potential as a tension* in the water. It indicates that plants must work against this tension to extract water from the soil. Wetting the soil releases the tension and water will move from the soil into the porous cup of the tensiometer.

The neutron probe is another tool used to measure soil-water content. The components of the system include a neutron source, a detector, an amplifier, and a scaler. The neutron source is placed in the soil at a desired depth and emitted neutrons strike hydrogen nuclei that are associated with water molecules. The scaler then senses the number of hydrogen nuclei and estimates water content of the soil.

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*"Tension" is the pressure required to extract water from soil and indicates the tenacity with which water is held in the soil.

TECHNOLOGIES

Soil-water supplies in the arid and semiarid region come mainly from two sources—precipitation and irrigation. Under each set of conditions, a distinct type of agriculture has evolved. Over large areas of the West, where soil-water supplies are derived from precipitation, dryland farming or rangeland agriculture is practiced. Where soil water is provided by supplemental water applications, irrigated agriculture is practiced.

The technologies described in this chapter are organized according to the type of agriculture for which they are most likely to be used. Where dryland farming or rangeland agriculture is practiced, methods that conserve precipitation are appropriate. On irrigated land, methods that manage supplemental water are applicable. Although each technology is discussed separately, effective use of precipitation or irrigation water often requires the use of more than one technology and skillful management of plants and soil.

Selection of technologies presented here was based on evaluations of a technology's ability to sustain agricultural productivity and potential use across broad geographic areas and in different types of agriculture. Although each technology will affect soil-water conditions to some extent, an estimate of the amount of water that could be conserved by adopting a particular practice is not presented. Reliable estimates are nearly impossible given the broad climatic, topographic, crop, and soil differences throughout the West, combined with uncertainty regarding the possible extent of application.

Conserving Precipitation

Technologies that conserve precipitation are aimed primarily at reducing water losses through surface runoff and evaporation (table 54). These goals can be achieved in three main ways. First, the soil surface can be shaped to hold water on the surface and facilitate water movement into the soil. Second, soil cover consisting of either growing plants or their residues can be managed to reduce runoff and evaporation losses. Third, soil properties such as structure or micro-organism content can be manipulated to conserve soil water. These practices also can be used together.

Shaping Soil Surfaces

INTRODUCTION

One of the most important features of a soil is its ability to take in water. For many centuries, farmers achieved improvements in infiltration by altering the soil surface or by reshaping the land. The ancient Egyptians plowed their fields to lift and loosen the top layers of soil to allow more water to infiltrate. Ancient people also used terraces, embankments built across a slope, to hold precipitation on the land.

In modern agriculture, the purposes and types of practices used to alter and reshape the land surface are similar to those used in the past. Today, however, many modifications have been made in the types of tools used and in the degree to which soil and vegetative cover are disturbed. For example, plowing, which is one step in seedbed preparation, has been replaced in many farming operations by minimum tillage, which leaves crop residues on the soil surface. Another practice, pitting, is ap-

Table 54.—Use of Precipitation: Technology, Application, and Effect on Soil Water

	Application			
Technology	Range	Dryland	Irrigated	Comments
Mechanical land treatments	X	X	X	Slow surface runoff, increased infiltration, facilitated water movement through soil
Terraces	X	X	X	Slow surface runoff, increased infiltration
Land grading or leveling	—	X	X	Slow surface runoff, increased infiltration
Mulches	X	X	X	Slow surface runoff, increased infiltration, slow evaporation
Plant-barrier systems	—	X	X	Slow evaporation conserves snow.
Modification of plant canopies	—	X	X	Slow evaporation
Mychorrizal fungi	X	X	X	Enhances plant-water uptake
Harvester ants and termites	X	—	—	Increased infiltration
Soil conditioners	—	X	X	Increased water retention

SOURCE: Office of Technology Assessment, 1982.

plied on rangelands. It uses a mechanical device to form small, shallow basins in the soil surface to hold precipitation onsite. In contrast, deep plowing, a practice used on croplands, completely inverts and mixes the soil layers to improve infiltration and water movement through the soil.

ASSESSMENT

Many land-shaping practices are effective in increasing the amount of water retained onsite for plant growth. In addition, these techologies can help conserve soil by reducing surface runoff. Generally, management requirements are low, and practices can be applied to rangeland, dryland, or irrigated areas.

The application of some practices is limited, however, by physical considerations. First, many technologies are site-specific; the water-conserving ability of each practice varies with soil type, topography, vegetation, and weather. Under natural rainfall conditions in arid areas, for example, these technologies will have little effect in improving soil-water conditions. A second limitation is the relatively short lifespan of some technologies. Some tillage practices (e.g., basin tillage) must be applied each time a crop is planted. Similarly, the storage capacity of pits diminishes rapidly, and pits may disappear within 6 to 10 years depending on site conditions. Finally, excessive working of the soil, coupled with the use of heavy machinery needed for application of some practices, can alter soil structure, thereby aggravating the soil conditions that these operations are trying to improve.

The application of land-shaping practices may be limited also by economic considerations. For some ranchers and farmers, the expense associated with applying these technologies (i.e., special equipment, labor, fuel, land taken out of production) may outweigh their benefits in increased forage or crop production. Furthermore, economic evaluations of costs and benefits that could assist farmers and ranchers in planning their operations are often not available.

Land-shaping practices may not be applied to grazing lands for other reasons. Often these lands are too arid, or on soils too shallow or too infertile, to realize an increase in forage production with their use. On more productive areas, some ranchers may object to mechanical treatments of natural grasslands because these practices have not been applied traditionally. Finally, on public rangelands, an individual who has a grazing permit may be prohibited from applying these practices.

Mechanical Land Treatments

Mechanical land treatments include such operations as deep plowing or ripping, land imprinting, contour furrowing, basin tillage, and pitting. In general, these practices alter the soil

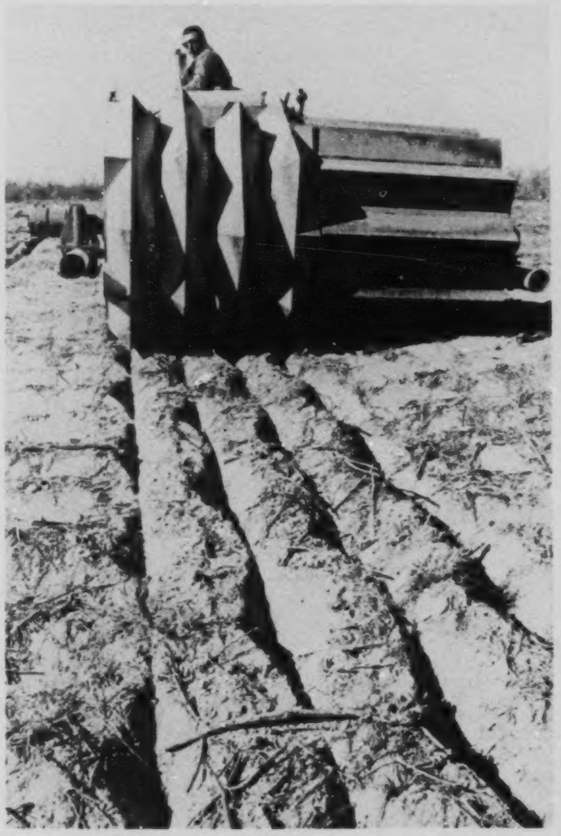


Photo credit: USDA-Agricultural Research Service

The land imprinter can help establish grass on near-barren areas. The imprinter presses furrows and seedbeds of varying depths on the soil. The patterns direct runoff rainwater and concentrate it where new grass is seeded.

structure and attempt to increase the amount of water retained onsite. Their application can aid plant establishment and can increase existing plant production.

Many mechanical land treatments are effective in conserving water and are used presently. Contour furrowing, for example, has been applied on rangelands in the Great Plains and Interior Basin and has been especially useful on sodium-affected soils to improve infiltration, reduce the sodium hazard, and increase herbage production. Contour furrows have an additional benefit in that they can catch more snow than can nearby unfurrowed areas. Another treatment, basin tillage, has been used in row-crop production in the southern Great Plains and has helped increase the amount of water stored in the soil. Deep ripping or plowing has been used on rangeland, dryland, and irrigated areas to break up compacted subsurface layers and to mix the different soil textures. Ranchers and farmers have reported increased forage and crop yields after this operation.

Extensive applications of mechanical land treatments are somewhat hindered by the site-specific nature of each technology. For example, some research indicates that pits are ineffective in areas of low precipitation and on clay soils (23,33). Where pits are used on range in poor condition, weed problems may develop. Ripping treatments on six Western range sites decreased perennial grass production, and researchers concluded that, in these areas, the relatively minor soil surface modifications did not have a marked effect on runoff or water retention (6).

Mechanical land treatments tend to have a limited lifespan. The storage capacity of pits and contour furrows diminishes rapidly with time, and basin tillage requires application each time a crop is grown. Where deep plowing is practiced, large soil pores and channels

Photo credit: USDA-Soil Conservation Service

Contour furrows are generally constructed to hold water onsite until it infiltrates the soil are difficult to maintain with subsequent tillage operations.

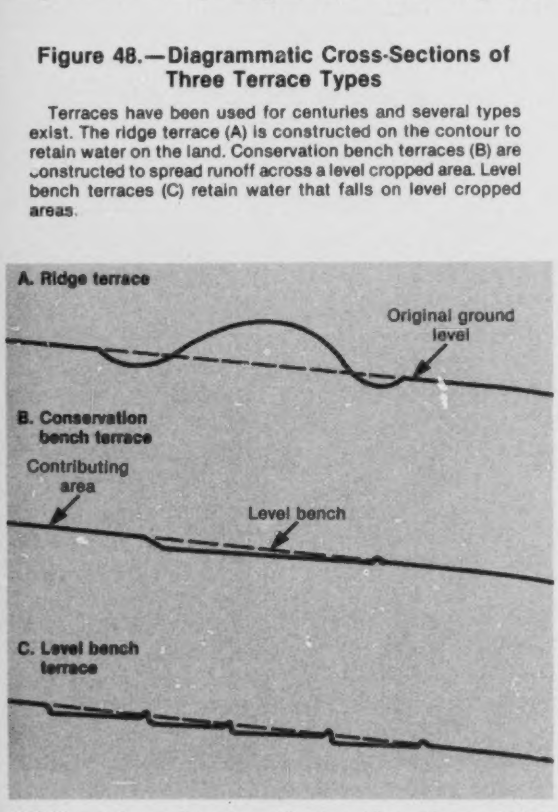
Finally, the application of these practices tends to be energy- and capital-intensive. Generally, special equipment is needed that may be too expensive for some operators. Equipment design also limits application of some practices. For example, basin tillage is limited currently to row-crop (e.g., corn, soybeans, and cotton) production, although it could be applied to close-growing, small-grains (e.g., wheat and barley) production if planting equipment were modified.

Terraces

Terraces are earthen embankments, channels, or combinations of embankments and channels built across the slope of the land (fig. 48). By reducing the length of a slope, terraces help conserve precipitation and irrigation water by reducing surface runoff. In addition, terraces trap snow and increase over-winter water storage. In semiarid regions, terraces have been used traditionally in dryland agriculture. Irrigators may also use terraces to reduce their irrigation water requirements.

Figure 48.—Diagrammatic Cross-Sections of Three Terrace Types

Terraces have been used for centuries and several types exist. The ridge terrace (A) is constructed on the contour to retain water on the land. Conservation bench terraces (B) are constructed to spread runoff across a level cropped area. Level bench terraces (C) retain water that falls on level cropped areas.



SOURCE: K. G. Brengle, *Principles and Practices of Dryland Farming* (Boulder, Colo.: Colorado Associated University Press, 1982)

Besides controlling runoff, terraces have other benefits. They help reduce soil erosion and sediment content in runoff water, improve farmability of sloping lands, and reduce peak runoff rates to installations downstream.

Several problems limit the use of terraces, however. One major difficulty is that terrace design has not kept pace with changes in farm machinery and maneuverability of farm equipment is sometimes difficult. A second problem is that construction generally entails the removal of topsoil from large areas and the use of heavy equipment. These two factors may combine to cause surface compaction and may result in reduced crop and forage production. Initially, construction may interfere with seasonal agricultural operations and uneven drying, ponding, and severe erosion in different parts of the same terrace channel are also common in the first 3 to 5 years after construction. Finally, during wet years, weed and insect control may be difficult.

Economic considerations may pose a barrier to the adoption of terrace systems. Terraces are often costly, although some technical and fiancial assistance may be available to producers for design and construction. Maintenance requirements are high, and labor and energy costs may increase more on terraced fields than on nonterraced areas. In addition, some land is lost from crop production because of the terraces.

Land Grading or Leveling

Land grading or leveling is a technology that consists of smoothing a field's surface to make it level. A leveled field allows more uniform water distribution, eliminates dry or waterlogged spots, and slows runoff. Currently, the practice is applied most often to irrigated fields but can be used on dry-farmed lands.

Although land leveling is effective for many areas, the technology is not suited to some fields. When first applied, leveling may reduce infiltration and accelerate soil erosion because the vegetative cover is disturbed and soil aggregates are destroyed. Second, some soils have a thin topsoil, and extensive leveling operations expose generally less productive subsoil. On these soils, to maintain productivity, topsoil may have to be set aside and spread back onto the site after the grading is completed. Finally, leveling operations may fill in low depressions, some of which are important to wildlife.

Application of land leveling is affected by a number of economic considerations, as well. Government agencies and irrigation districts may have technical and cost-share provisions for land leveling on irrigated land that can reduce water costs, increase crop yields, and improve farm profits. For most dryland crops, however, the benefits derived from land leveling do not pay for its application. Laser leveling is particularly expensive at present.* Basic laser equipment costs from $12,000 to $20,000, and scrapers that can be laser controlled range in cost from $9,000 to $30,000 (17).

Managing Soil Cover

INTRODUCTION

Agricultural practices often have dramatic effects on the ground cover and consequently on soil and water relationships. This relationship has been long recognized by agriculturalists. In semiarid regions of the West, for example, early proponents of fallow systems (a type of dryland farming in which, generally, a crop is harvested every 2 years) believed that a covering of soil, or "dust mulch," left on the surface in alternate years would prevent water from evaporating from the surface. Although these claims were valid to some extent, wind tended to blow away the mulch and the amount of water conserved was negligible.

Technologies that affect soil cover aim to reduce surface runoff, increase infiltration, and reduce soil erosion. These practices include plant-residue management, application of materials that act like plant residues, and manipulation of growing vegetation (see box R).

ASSESSMENT

Managing soil cover is an effective means to increase the efficiency of precipitation storage, but several limitations to their use exist. First, management requirements are high. With improved soil-water conditions, weeds and other crop pests may build up and require control by mechanical or chemical means. Second, soil covers may lower soil temperatures and reduce seed germination, a consideration in cooler regions. Third, these practices are largely limited to dryland and irrigated regions because of the economics of their application and maintenance.

Mulches

Surface mulches are protective soil coverings that are spread or left on the soil surface and used to increase infiltration, decrease surface runoff and erosion, and slow evaporation losses.* They can be used in irrigated, dryland, and rangeland agriculture, and consist of crop residues applied where they are produced or of introduced layers of plant materials, gravel, black plastic, or sewage sludge.

Residual Mulches.—The use of crop residues as surface mulch became a common practice during the 1930's to reduce the effects of wind and water erosion. Since then, farming practices and equipment have been developed to till the soil and plant crops without inverting or burying the residue. On rangeland, slash or debris from brush and trees are used as mulch.

The value of mulch for collecting and storing available precipitation in dryland agriculture has been documented by numerous inves-

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*Traditional land-surveying techniques that determine the extent of leveling needed, have been replaced in some areas by laser-controlled devices that permit more precise leveling and provide for more uniform distribution of water.

*Depending on the amount of crop residue available, some nontranspiring vegetation, such as standing wheat stubble, can reduce evaporation losses. However, if plant residues are scant, as in many arid and semiarid areas, the reduction in evaporation is minimal.

Box R.—Conservation Tillage: A New Way to Farm?

Prior to the 1940's, farmers relied on a variety of tillage practices to prepare a seedbed, control weeds, and bury plant residues. With the advent of chemical herbicides, many producers began to substitute chemical weed control and "conservation tillage" for some of the traditional tillage operations.

Although conservation tillage has attracted much attention in recent years, the practice is quite old. In 1814, James Hall of Virginia secured a patent for a method of planting corn in an unplowed field. He marked the land in squares; each square was a certain dimension and distance from other plots and contained a given number of corn plants. Only these squares were cultivated, manured, and mulched; the rest of the field remained in grass. Hall had little success with his idea. The corn was unable to withstand dry weather, and many farmers criticized the practice as slovenly.

The term "conservation tillage" is inexact in meaning. Generally, the practice uses fewer operations to produce crops than does conventional tillage. Three other characteristics distinguish conservation tillage: it uses implements other than the moldboard plow; it leaves residues on the soil surface; and, it depends primarily on herbicides for weed control, although the degree of dependence on herbicides varies.

In the arid and semiarid region, conservation tillage is important, especially for its use in conserving water and soil. Small-grain producers can find its application particularly beneficial, and the advent of large chisel-type air seeders that can plant large acreages in a short period of time has made conservation tillage profitable for these farmers. Conservation tillage has lower farm labor and preharvest fuel requirements than does conventional tillage. It can be used on sloping lands and can enable some producers to plant more than one crop in a season (multiple-cropping) or omit the fallow period (continuous cropping).

These advantages are countered by several physical and economic constraints that include high management requirements needed for control of weeds and other pests and for fertilizer placement, high costs of herbicides, adverse effects of herbicide use on human health and the environment, limited application in some cool dryland regions and some irrigated areas, high costs of seeding equipment, and availability of plant varieties that will germinate in thick residue.

SOURCE: William T. Dishman, advisory panel member, personal communication, 1983; Hayden Ferguson, William Lyle, Charles Fenster, and Charles Wendt, *Dryland Agriculture*, OTA commissioned paper, July 1982; *Impacts of Technology on U.S. Cropland and Rangeland Productivity* (Washington, D.C.: U.S. Congress, Office of Technology Assessment, OTA-F-166, 1982); Andrew C. Revkin, "Paraquat—A Potent Weed Killer is Killing People," *Science Digest* 91:36-38,42,100-104, 1933.

tigators (11). Mulch reduces runoff and tends to increase soil-water storage by protecting the soil surface from the impact of precipitation and by allowing more time for infiltration to occur. In colder regions, standing stubble mulch traps snow. Additional benefits include higher crop yields, increased soil organic-matter content, more stable soil aggregates, and decreased wind and water erosion.

Mulches are used widely in dryland crop production but less extensively on rangeland and irrigated fields. On rangeland, a lack of plant residues restricts application to critical areas—e.g., surface-mined sites or saline-affected soils (34). On irrigated land, mulches are used most often under sprinkler irrigation systems. Farmers who attempt to use mulches in surface irrigation may experience difficulty in getting supplemental water through a field (13).

Crop residues also are difficult to maintain because relatively low amounts are produced in most dryland areas and a large portion is destroyed during tillage operations. For example, stubble-mulch tillage, a method of cultivation practiced widely in small-grain production, attempts to maintain surface residues through each tillage operation. However, this practice destroys approximately 15 percent of

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Photo credit: USDA-Soil Conservation Service

A no-till drill, designed by the University of Idaho, used on an Idaho farm. No-till is one form of conservation tillage to reduce soil erosion and soil-water loss (see Box R)

the residue each time; over a fallow period, stubble-mulch tillage will destroy about 75 percent of the original residue (11).

Weeds and insect pests may build up when crop-residue mulches are used. In addition, in cooler dryland regions—e.g., the northern Great Plains and the Pacific Northwest—crop yields are sometimes lower under a residue mulch than would be expected, considering the amount of water available. Cool soil temperatures during critical stages of crop growth or reduced levels of nitrates during certain periods of the year are possible reasons for yield reductions.

Another limitation to the use of crop-residue mulches to conserve available water is the increased risk of development of saline seeps (fig. 49). This is a hazard especially in the northern

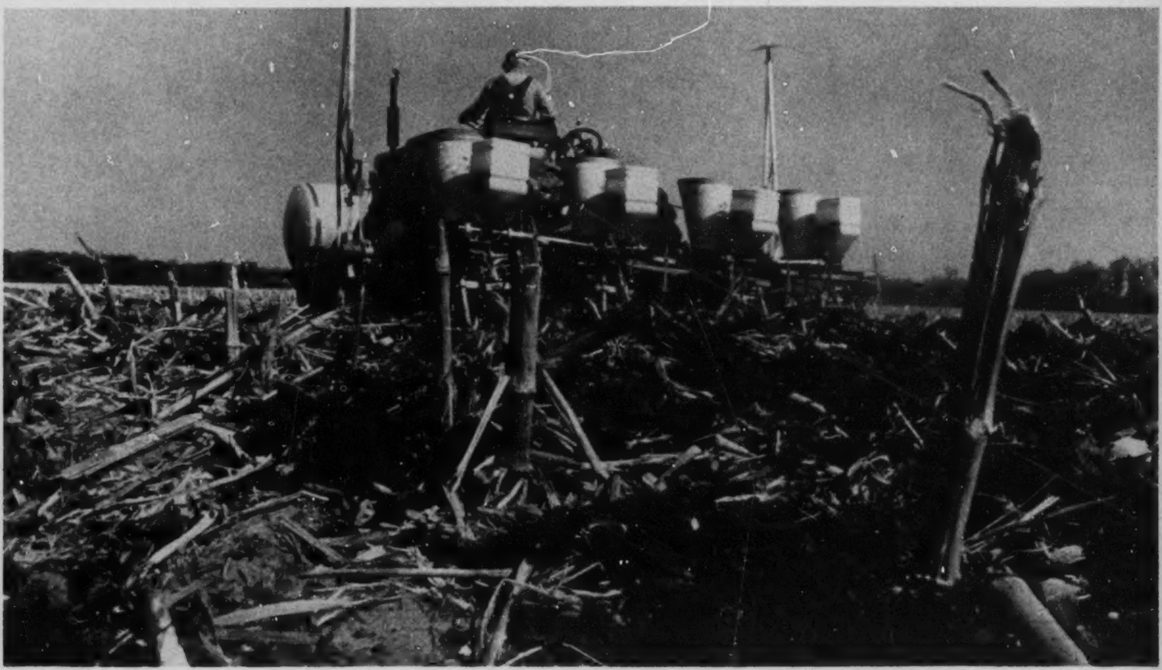
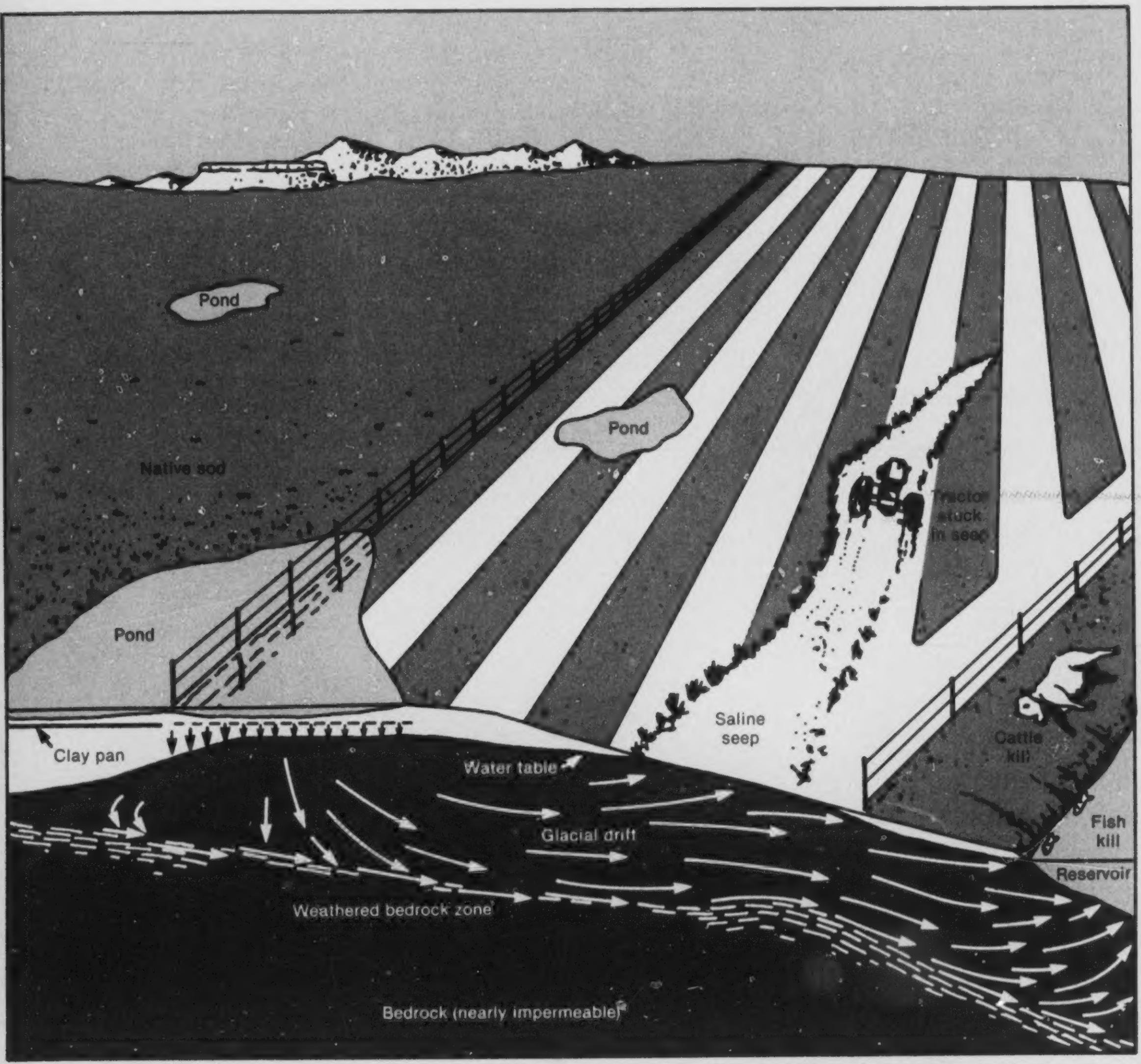


Photo credit: USDA-Soil Conservation Service

Minimum till planting in corn stubble, Gage County, Nebr. (see box R)

Figure 49.—Development of a Saline Seep


Pond
Pond
Native sod
Tractor stuck in seep
Pond
Saline seep
Cattle kill
Clay pan
Water table
Glacial drift
Fish kill
Reservoir
Weathered bedrock zone
Bedrock (nearly impermeable)

Saline seeps form when soil water percolates downward beneath the root zone, picks up soluble salts in the soil, and accumulates on shallow, less permeable soil layers. A perched water table forms, and lateral flow then moves saline water from recharge to discharge areas, where it evaporates and leaves a salt deposit on the soil surface. These areas, often identifiable by a white salt crust on the soil surface, tend to reduce or eliminate crop and grass production, and the consumption of salts may result in animal kills.

SOURCE: M. R. Miller, P. L. Brown, J. J. Donovan, R. N. Bergation, J. L. Sonderegger, and F. A. Schmidt, "Saline Seep Development and Control in the North American Great Plains — Hydrogeological Aspects," *Agric. Water Manage.* 4:115-141, 1981.

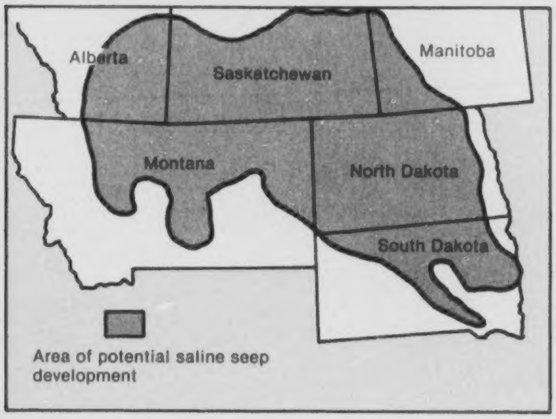
Great Plains (Montana, North and South Dakota), where a wheat-fallow rotation is followed, because of the geology and climate of the region (fig. 50). Black, et al. (5), estimate that 2 million acres (approximately 800,000 hectares) of land used for dryland agriculture have been affected by saline seeps. (Ch. XI discusses flexible cropping, a possible way to reduce this hazard.)

Introduced Plant Residues and Artificial Materials.—Introduced materials used for mulching have comparable purposes as residue mulches. Materials vary; straw (grain stalks after threshing) and wood chips, sewage sludge, gravel mulches, and black plastic have been used.

Introduced mulches are used in both rangeland and dryland farming regions with success. Mulches have been especially useful on rangeland to help in reseeding and plant establishment efforts. In dryland regions, Choriki (8) showed that layers of "pea" gravel about 2 inches deep on the soil surface increased the storage efficiency of summer precipitation by some 60 percent and made annual cropping feasible in the low rainfall area.

The major limitations of introduced mulches are similar to those associated with residual mulches—e.g., cooler soil temperatures that may inhibit seed germination and accelerate plant pest buildup. In addition, introduced mulches are sometimes difficult and expensive to acquire, transport, apply, and maintain. The ability to reverse the effects of an introduced mulch, especially gravel or sewage sludge, has been questioned (24).

Figure 50.—Areas of Potential Saline Seep Development, Northern Great Plains Region



SOURCE: Office of Technology Assessment, *Impacts of Technology on U.S. Cropland and Rangeland Productivity* (Washington, D.C.: U.S. Government Printing Office, 1982).

Plant-Barrier Systems

Growing plants can be used to conserve soil and water that might otherwise be lost because of the drying effects of wind. The types of plants used as barriers vary; historically, rows of trees and shrubs (shelterbelts) have been used. More recently, research has focused on incorporating single and double rows of relatively low-growing vegetation (e.g., wheatgrass, sorghum, or corn) within a field to catch snow, reduce windspeed near the soil surface, reduce evaporation from wet soil, and control wind erosion.

Plant-barrier systems are used mainly in semiarid dryland farming areas that rely on snow to supply soil water. The barriers are especially useful in conserving snow during the second winter of a fallow period. The subsequent increase in soil water can boost crop production and may be sufficient to permit annual cropping.

Limited research indicates that plant barriers can also be applied to rangeland. Grass strips planted between low-growing sagebrush vegetation increased onsite snow retention and contributed to increased soil water and improved site productivity (30).

Plant barriers also have other benefits. Tree barriers provide protection from wind erosion and are pleasing esthetically. Annual vegetative barriers and shelterbelts also can provide cover and food for wildlife.

Although plant barriers are an effective way to conserve snowfall, several considerations may restict their adoption. First, it is sometimes physically difficult to get water into frozen soil once the snow begins to melt. In the northern part of the Great Plains, for example, soils freeze deep and "hard." Moreover, these soils

Photo credit: USDA-Soil Conservation Service

This farmstead windbreak includes a variety of plants, both trees and shrubs. Besides conserving snowfall, the windbreaks protect against wind erosion, provide wildlife with food and cover, and are esthetically pleasing

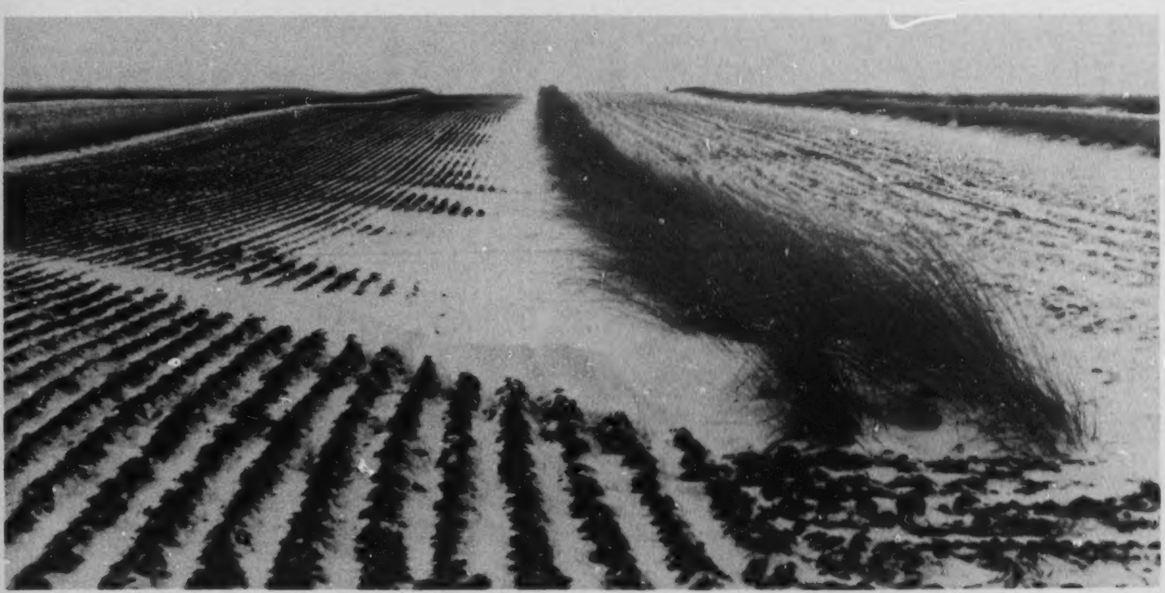


Photo credit: USDA-Soil Conservation Service

Tall wheatgrass barriers control wind erosion and trap snow to increase stored soil water. Tall wheatgrass barriers reach an average height of 4 ft and snow accumulates relatively uniformly across the interval between barriers are often wet when they freeze. As a result, storage efficiency of the soil is often low and serious erosion and water loss problems can occur. Occasional midwinter warm periods have a similar effect. In these areas, tillage operations may be needed to roughen the soil surface to trap snow and snowmelt water and to allow water movement into the frozen soil.

Other constraints on adoption of plant-barrier systems include:

- accelerated wind erosion if plants are not spaced properly;
- buildup of crop pests—e.g., weeds and insects—and difficulty in control;
- loss of some cropland;
- disease problems in some areas, especially in northern Washington and southeastern Idaho, where snow mold can develop and affect winter wheat;
- soil-water use by noncrop plants;
- uneven grain ripening (especially where annual barriers are planted) unless barriers are spaced properly to ensure uniform snow distribution; and
- soil compaction where annual barriers force tillage operations in the same direction and on the same path.

Modification of Plant Canopies

To reduce the amount of evaporation that occurs early in the growing season, two approaches have been developed to allow for earlier canopy closure: increased plant density and modified plant spacing. These measures are especially effective in reducing evaporation losses in areas of frequent rainfall early in the growing season or of frequent irrigations that are required because of soil texture and depth. Modifications in plant canopies can also reduce wind velocities near the soil surface and lessen evaporation losses. Such practices can result in a slight increase in yield because of the higher plant populations.

Widespread application of these systems is hindered by two considerations. First, under high water-stress situations, close-growing crops may suffer yield reductions. Second, if tall and short varieties are combined in a field to reduce wind velocity, height difference may become insignificant when plants are water-stressed (10).

Changing Soil Properties

INTRODUCTION

Besides mineral and organic constituents, soils include a living component that consists of a diverse population of micro-organisms such as bacteria, fungi, algae, and protozoa; small invertebrate animals such as earthworms, ants, and termites; larger vertebrate animals like snakes, moles, gophers; and birds, such as burrowing owls. This diversity in animal and plant life accounts for the varied role the living component plays in soil and plant processes. For example, some micro-organisms cause plant disease. More importantly, however, they decompose dead plants and animals, recycle plant nutrients, and play a critical part in forming the humus that binds minute soil particles into larger aggregates. Humus aids in water infiltration and retention and plant-root development. Soil animals may also assist in improving water relationships by mixing the soil profile and by breaking up hard subsurface layers.

Amendments* added to soil can affect soil and water relationships. For example, chemical fertilizers appear to stimulate plant root growth and aid soil-water extraction. Chemical soil conditioner materials (other than conventional fertilizers) that are added to soils to change them physically, chemically, or biologically, imitate the action of living organisms and increase the amount of water retained in soils. Plastic sheeting or gravel can be buried within sandy soils to assist in retaining water for plant growth.

ASSESSMENT

The potential for changing soil properties to improve soil-water retention by using biological organisms or other amendments is unclear and more research is needed. These technologies seem to have some application on small areas with special problems, but, generally, questions about their longevity, effectiveness under different climates and variable field conditions, economics of use, and other possible effects have not been resolved.

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*Substances that aid plant growth indirectly by improving the condition of the soil.

Mycorrhizae

Mycorrhizal fungi are beneficial soil microorganisms that form symbiotic associations with the fine feeder roots of plants. By colonizing the plant root, the fungi receive an energy source, nutrients, and other plant chemicals from the host. Generally, the plant benefits from improved uptake of mineral nutrients (particularly phosphorus) and water. Ninety-eight percent of all plant species form mycorrhizal associations and most require symbiosis for maximum growth and survival (12).

Mycorrhizal fungi may play an important part in agricultural production in arid and semiarid regions. Research shows that plants colonized by these fungi seem more tolerant of dry conditions, have increased resistance to the toxic effects of salts, and have improved tolerance to numerous root pathogens (e.g., 14, 19,27). Also, mycorrhizae have been shown to improve the growth and survival of plants introduced into arid and semiarid lands by 20 to 200 percent (e.g., 1,7). The mechanisms that underlie these effects are not understood fully. Improved mineral nutrition of the host is thought to be a dominant influence, but osmotic and hormonal adjustments to infection may also be involved.

Potentially, two important applications of mycorrhizal inocula exist. The first involves rebuilding depleted populations of mycorrhizal fungi in soils that have been disturbed by soil erosion, surface mining, fire, fumigation, or long-term cropping with nonmycorrhizal species. Plants grown on such soils are frequently stunted and may benefit from mycorrhizal inoculations. The second application is associated with transplanted horticultural crops. Mycorrhizal inoculation can reduce transplant injury and increase growth and establishment of some nursery crops (4,21).

Despite their potential utility, commercialization and use of mycorrhizal inoculants are limited at present. Major obstacles include problems in development of commercial culture systems for inoculum production, risks associated with inocula that may carry disease, lack of efficient field inoculation techniques, lack of guidelines for predicting costs and benefits of inoculations, and the need for identification of superior and versatile fungal strains.

Harvester Ants and Termites

Western harvester ants and termites are regarded as pests of economic importance on many Western range sites. They frequently denude an area of existing vegetation through forage and mound activities.

Limited research indicates that dry matter yields in the area around ant colonies and termite mounds are much higher than in adjacent areas (3,28). Researchers speculate that vegetation removal by the ants and termites increases soil water in the mound area and its border. In addition, ant and termite activity may be beneficial to the physical and chemical character of the soil and may increase infiltration and soil-water storage.

The potential for this technology is unknown. Most range managers view these insects more as a detriment than a benefit to rangeland. Their future use appears restricted to small, local sites.

Soil Conditioners

Soil conditioners, also known as soil amendments and soil additives, are materials other than conventional fertilizers that are added to soils to change them physically, chemically, or biologically to improve productivity. In the arid and semiarid regions, most attention has focused on the use of these substances to increase the amount of water retained in soils that have low water-retention capacities.

Some chemical amendments, such as water-holding starch copolymers ("super-slurpers," H-SPAN) have shown a tendency to increase water retention in sandy soils. Naturally occurring zeolite minerals have also been used to increase soil water-holding capacity.

Widespread use of chemical conditioners has been hampered by many scientific, economic, and legal considerations. Generally, research is lacking on their application. Zeolites have not attracted widespread attention from agricultural researchers in the United States. Use of expensive soil conditioners is limited to special soil conditions and to high-value crops. Finally, because of unfavorable experience with chemical soil conditioners in the past, some States have taken legal action to require scientifically acceptable evidence for efficacy before these products are offered for sale within the State.

Supplementing Soil-Water Supplies

The primary purpose of irrigation is to supply water to crops during periods of water shortage. The practice lessens some seasonal risks associated with farming, allows production in areas that could not produce most crops otherwise, and gives producers greater flexibility in selecting crops to be grown. Also, irrigation can boost crop yields.

Irrigated agriculture plays a significant role in modifying natural resources. Some of these

Box 8.—Irrigation and Soil Erosion

Many people assume that soil erosion in the arid and semiarid region is limited to overgrazed rangeland and dryland agriculture. Irrigated lands are considered to be free of this hazard. For example, the Soil Conservation Service's (SCS) 1977 National Resources Inventory estimated that erosion on irrigated row crops averaged approximately 3 tons/acre/yr. The national average on all cropland was about 7 tons/acre/yr. (Soil conservationists generally recommend that soil losses not exceed 5 tons/acre/yr.)

Some irrigated lands do have little erosion. For example, surface irrigation in an enclosed basin (basin irrigation) usually results in no net soil loss to the field and minimal soil transfer within the basin. Often, however, erosion in other types of surface systems and on sloping lands are much higher. A study by SCS in Idaho (Hazleton Butte Watershed) found that on fields with slopes of 0 to 4 percent and under furrow irrigation, erosion averaged 8 tons/acre/yr. Winter erosion added another 15 tons/acre/yr.

One of the reasons that soil erosion on irrigated land has been discounted is that it is hard to measure. Erosion depends on soil, slope, climate, and agricultural management, including the type and management of the irrigation system (e.g., length of run, set time, and number of sets in a field). Furthermore, within a single field, soil loss can vary from irrigation to irrigation. For example, early season irrigations can be more erosive than later irrigations because the furrows are unstable and susceptible to the erosive force of water. Another factor that makes erosion difficult to measure is that under some types of irrigation, the process of soil erosion is fundamentally different from the process that occurs under rainfall. Because of these discrepancies, the usual method of estimating soil erosion on cropland (Universal Soil Loss Equation) is not accurate on irrigated lands.

A number of practices can be adopted to reduce erosion on irrigated land, and some erosion control methods are also water-conserving operations. Conversion from furrow irrigation to sprinkler irrigation, installation of sediment traps, or simpler operations such as planting a filter strip of grain across the top or bottom of a furrow-irrigated field, or reducing the amount of water running through the furrow once it has been wetted, can cut erosion losses. If weeds can be controlled, conservation tillage on irrigated lands is another possible option. If soil savings can be combined with improved profitability—higher crop yields or lower operating costs—farmers will be more likely to adopt these practcies.

SOURCE: Excerpted from: Neil Sampson, "Soil Erosion and Irrigation," paper prepared for the American Farmland Trust Study on Soil Conservation Issues, Mar. 1, 1983.

effects—depleted water supplies, altered streamflow conditions, and degraded water quality—have been discussed in other chapters. A major problem affecting irrigated soils is salinity, although soil erosion and nutrient content of irrigated crops are concerns as well (e.g., 22,26).

Soil salinity is often associated with irrigated agriculture although nonirrigated lands can also be affected.* Salinity is a special hazard in the Western States; van Schilfgaarde (32) estimates that 25 to 35 percent of the irrigated cropland in the region is affected by high levels of salinity and that the problem is growing. Furthermore, the costs of damage to both farmers and municipal and industrial users are enormous. The Bureau of Reclamation, for example, has estimated that the annual cost of damage in the Colorado River Basin is $100 million and will escalate to $237 million per year in 2000 (in constant 1981 dollars) (2). The process of salinization is considered in this section because excessive salt concentrations can interfere with plant-water uptake. Under these conditions, a plant can show signs of water stress even though the soil is wet and crop yields can be lowered.

Soil salinization can occur in two ways—either insufficient irrigation water is applied or drainage is inadequate. In the first case, as irrigation proceeds and water (containing salt) is added to the soil, pure water evaporates or is transpired by plants, and salts remain in the soil. Soil weathering, accelerated by irrigation, also contributes salts to the soil solution. Unless these salts are periodically flushed by rain or by excess application of irrigation water, the salt content of the soil will gradually increase and soil salinization will occur. In the second case, where drainage is inadequate, salinization occurs as repeated irrigations raise the ground water table and capillary rise carries water close to the soil surface where it evaporates, leaving a salt residue.

Photo credit: USDA-Soil Conservation Service

In California's Imperial Valley, soil-salinity levels on irrigated land pose a major limitation to crop production. This alfalfa crop has been reduced severely by salt buildup

Leaching, whether by periodic flushing or adequate irrigation, can mitigate the effects of salinization. However, large water applications require adequate drainage (sometimes a network of drains must be installed across a salt-affect area) and often increases the salt concentrations for downstream users. If smaller quantities of water are used for leaching, a crop's tolerance to increased salinity in the lower part of the root zone must be considered and monitoring is necessary. As stressed by Rhoades (25):

> At present we do not have suitable inventories of soil salinity in this country nor do we have operational monitoring programs to follow the salinity status in our soils . . . The prop-

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*In salinization, a soil accumulates sufficient soluble salts to impair its productivity. These salts mostly consist of various proportions of the cations (positively charged ions) sodium, calcium, and magnesium, and the anions (negatively charged ions) chloride and sulfate.

er operation of a viable, permanent irrigation agriculture that is also efficient in water use requires periodic information on the salinity levels and distributions present within the rootzones of the soils of irrigation projects. Only then can the adequacy, effectiveness, and efficiency of the projects' operations be validly assessed with respect to salt balance.

Other management methods to cope with soil salinity include precise land leveling of fields to enable flood, rather than furrow, irrigation so that infiltration is more uniform and dissolved salts are transported below the root to the drainage system with a minimum of applied water. Where land leveling is impractical, sprinkler irrigation may be needed. In both cases, irrigation must be scheduled with smaller quantities of water at each irrigation and at more frequent intervals to maintain downward movement of salts and favorable growing conditions for the plant, especially during germination and seedling stages.

Onfarm salinity management is costly and many farmers may not have the capital necessary for such practices. One estimate placed the cost for a sprinkler irrigation setup at about $500 per acre. Precision land leveling was estimated at $50 to $100 per acre (15).

Defining Irrigation Terms

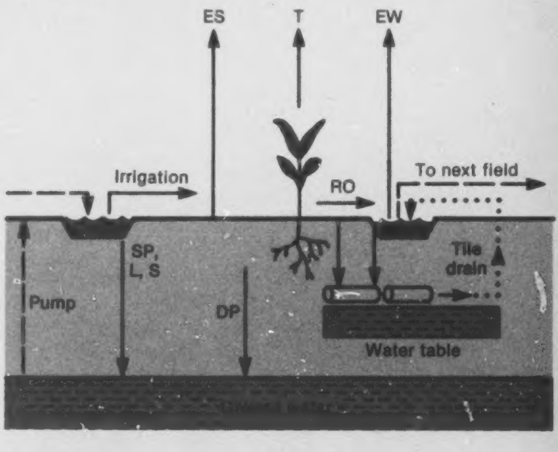
Farmers are encouraged often to "save" irrigation water, but this term and its effects on the individual and on total water supplies are sometimes unclear. First, this section defines some of the terms associated with irrigation water management and then discusses how onfarm water conservation affects an individual irrigator and regional water supplies.

Technologies that affect irrigation practices are often discussed in terms of their "onfarm irrigation efficiency," defined as the ratio, or percentage, of the volume of water stored in the soil root zone and used by the crop to the volume of water delivered to the farm (31). Onfarm irrigation efficiency characterizes the onfarm distribution system and the field-application system.

After irrigation water is applied, water that does not become a part of soil moisture supplies in one field (this component includes seepage, surface runoff, and deep percolation) remains part of an area's total water supply and is usually available for reuse downstream, although pumping may be required and water quality may be changed significantly. These losses are termed "recoverable." Losses that result from evaporation from open water, and from the soil surface, transpiration, and flows to saline sinks are called "irrecoverable" since they are lost except through the course of the hydrologic cycle or costly desalination operations (fig. 51).

Surface runoff and deep percolation can be curtailed in several ways, resulting in higher onfarm irrigation efficiencies. In most cases, however, a roughly equal reduction in return flows occurs, and a small net water savings is realized (fig. 52) (9).

Figure 51.—Water Destinations in a Cropped Field



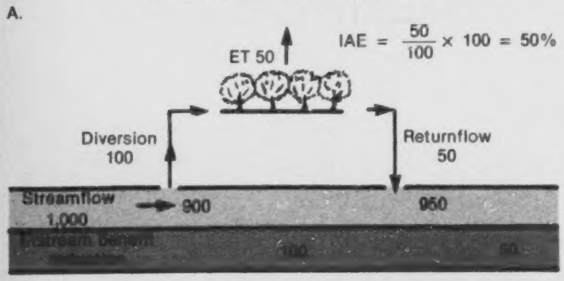
Key

Recoverable losses:
S—Seepage
L—Leakage
SP-Operational spills
RO-Surface runoff
DP-Deep percolation

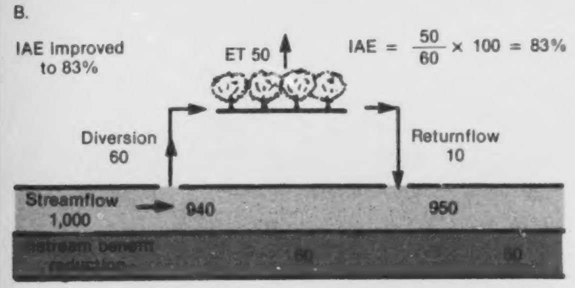
Irrecoverable losses:
EW-Evaporation from open water
ES-Evaporation from soil
T—Transportation

SOURCE: David C. Davenport and Robert M. Hagen, *Agricultural Water Conservation in California, With Emphasis on the San Joaquin Valley*, Technical Report, Department of Land, Air and Water Resources, University of California, Davis, 1982.

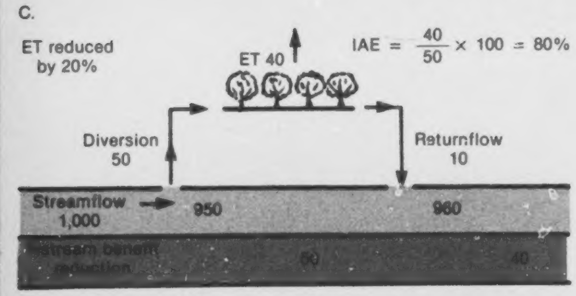
Figure 52.—Effects of Agricultural Water Conservation on Streamflow



These illustrations show in a simplified way, the interrelations among water supply, gross demand, and return flows. In figure A, 100 units of water are diverted from a 1,000-unit supply of streamflow. 50 of the 100 units are lost as evapotranspiration (resulting in an onfarm irrigation efficiency of 50%). 50 units are returned to the water source as return flow, thereby yielding a final streamflow of 950 units.



In figure B, the farming area has improved its irrigation efficiency to 83%. Still meeting crop needs for water of 50 units, only 60 units of water (instead of 100 units) need to be diverted. Streamflow is reduced to 940 units between points of diversion and outflow and 10 units are returned to the source. Final streamflow remains at 950 units.



In figure C, the evapotranspiration requirements of the agricultural area are reduced from 50 units to 40 units. Because ET is smaller, less water diversion is needed (50 units instead of 60 units). The smaller diversion results in a streamflow of 950 units between the points of diversion and returnflow; final streamflow is 960 units (instead of the 950 units in the other examples).

(ET = Evapotranspiration; IAE = Irrigation Application Efficiency)

SOURCE: David C. Davenport and Robert M. Hagen, *Agricultural Water Conservation in California, With Emphasis on the San Joaquin Valley*, technical report, Department of Land, Air and Water Resources, University of California, Davis, 1982.

Reduction in irrecoverable losses are generally harder to achieve but can result in a reduction in net water consumption. Evaporation losses, for example, can be reduced most easily by preventing unnecessary wetting and exposure of the soil surface. In many areas, the effort required to reduce evaporation is not worthwhile in relation to the amount of water saved. Furthermore, a reduction in evaporation losses can increase temperatures and reduce humidities at the surface and result in greater transpiration losses. Crop transpiration losses are especially difficult to control. Producers can decrease crop acreage and thereby curtail total transpiration losses, grow crops that mature in a shorter time, or use antitranspirants but these measures are usually not economically feasible for most producers.

To assess the effect of irrigation water conservation on total water supplies, a study by the Soil Conservation Service looked at several irrigation water conservation measures, both on and off the farm, and evaluated their potential for reducing irrigation water demands in the 17 Western States (31). With no increase in either irrigated acreage or volume of water provided to water-short areas, improved irrigation efficiencies reduced irrigation diversions by over 30 million acre-ft. However, the water that was available for reallocation was estimated at only 3.3 million acre-ft.

Other than saving some quantity of water, onfarm water conservation efforts have both benefits and negative consequences for an individual and for a wider area. Advantages of reducing recoverable losses include energy savings by reduced pumping requirements, plant-nutrient savings by reducing leaching losses, less nutrient pollution and salt emission to surface and ground water, fewer plant disease and weed problems, less standing water from runoff where mosquitoes could breed, and increased instream flows in sections of rivers where water diversions are reduced. The disadvantage of reducing recoverable water losses is that less water is available for leaching salts from the soil, ground water recharge, and wildlife habitat.

Advantages for reducing irrecoverable losses include reduced draft requirements for both surface and ground water, energy savings from lowered pumping requirements, increased streamflow, additional water for other agricultural and municipal and industrial uses, and improved quality of subsurface water. Reduced crop yields and the physical requirements needed to implement measures to reduce evapotranspiration losses are major disadvantages.

Finally, physical, social, legal, and economic factors often hinder adoption of practices that could improve onfarm irrigation efficiencies. These include:

- onfarm physical conditions that cannot be alleviated easily (e.g., sandy soils that have low retention capacities);
- difficulties in identifying practices that reduce irrigation efficiencies because of current measurement techniques and services;
- relative insignificance of water losses to an individual if water is inexpensive or cannot be used if saved;
- questions over costs of practices relative to benefits derived from application;
- feasibility of integrating new practices into existing farm management practices; and
- legal uncertainties regarding whether the farmer can use the water "saved" (see ch. V).

The following sections discuss various modifications to existing irrigation systems and possible irrigation strategies that individuals can use to "stretch" their water supplies.

Supplying Full Water Needs to Plants

INTRODUCTION

Traditionally, irrigation systems are designed and operated to supply full water needs to plants so that yields are not limited by water shortages and yields are maximized per unit area irrigated. The crop root zone, the depth of soil where crop roots are actively growing (usually 1.5 to 6 ft deep), provides a reservoir for storing water until it is needed for plant growth. Water that infiltrates the soil but exceeds its storage capacity will percolate below the roots and will enter the ground water.

ASSESSMENT

In irrigated areas of the West, three major types of irrigation systems are used to apply water. The most widespread type is gravity or surface flow, followed by sprinkler irrigation, and drip or microirrigation (table 55). A fourth type, subsurface irrigation, is used less frequently. Each system is best suited to specific soil, topography, crop, climatic, and economic conditions. For example, surface methods are generally the least expensive type of irrigation, in capital required for application, but they require larger flow rates to operate efficiently than do sprinkler or drip methods. If less efficient, surface methods require larger gross applications of water than do sprinkler or drip irrigation. Sprinkler methods are well suited to steep or rolling lands but often require substantial investments in equipment. Drip irrigation is appropriate for orchard and horticultural crops but less suited to row crops like corn or cotton. It also requires large capital investments.

Technically, most irrigation systems have similar field application efficiencies. However, actual application efficiencies vary considerably and range from less than 40 percent in areas where management and site conditions

Table 55.—Irrigation Methods, 17 Western States, 1981

	Type of irrigation (in percent)		
State	Surface	Sprinkler	Drip
Arizona	93.6	6.0	0.4
California	77.0	20.0	4.0
Colorado	78.0	22.0	—
Idaho	73.0	27.0	—
Kansas	63.0	37.0	—
Montana	92.0	8.0	—
Nebraska	57.0	43.0	—
Nevada	95.0	5.0	—
New Mexico	87.9	12.0	0.1
North Dakota	23.0	77.0	—
Oklahoma	48.9	51.0	0.1
Oregon	46.9	53.0	0.1
South Dakota	13.0	87.0	—
Texas	72.7	27.0	0.3
Utah	77.9	22.0	0.1
Washington	28.8	71.0	0.2
Wyoming	90.0	10.0	—

SOURCE: Marvin Jensen, *Overview-Irrigation in U.S. Arid and Semiarid Lands*, OTA commissioned paper, 1982. (Original source: *Irrigation Journal*, December 1981).

are poor to over 80 percent in a well-managed system under good field conditions (fig. 53). Reasons for low onfarm irrigation efficiencies are outlined in table 56.

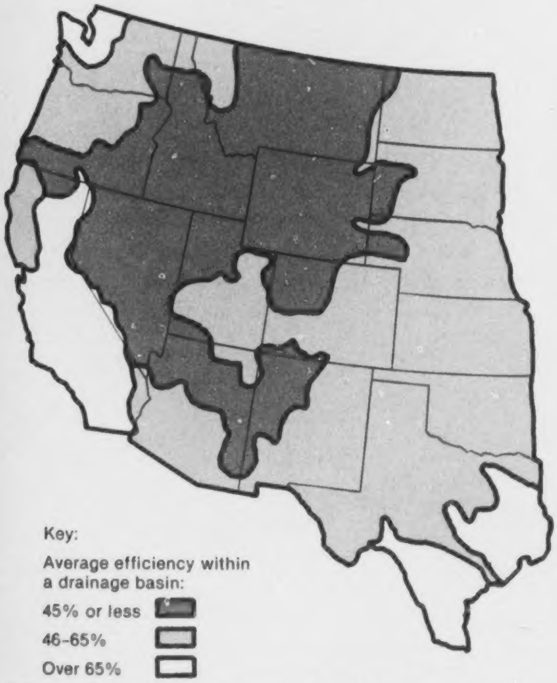
Surface Irrigation

Surface irrigation refers to irrigation methods where the soil surface serves both as the channel to distribute the water over the field and the control for water entry (fig. 54). Gravity provides the energy needed to distribute the water. Surface irrigation may be further subdivided into: 1) flooding, and 2) furrow irrigation.

Numerous modifications to existing surface irrigation operations can be made by irrigators to reduce evaporation and deep percolation losses and runoff. These include:

- manipulation of the length of time water is applied (set time), irrigation stream size, irrigation frequency, and the distance over which water is applied (length of run);
- land smoothing or leveling; ditch lining; surge flow (a method of water application);
- automation; and
- system replacement.

Figure 53.—Onfarm Irrigation Efficiencies, 17 Western States



SOURCE: U.S. Department of Agriculture, *Soil and Water Resources Conservation Act*, 1980 Appraisal, pt. II, 1981.

Table 56.—Factors Reducing Onfarm Irrigation Efficiency

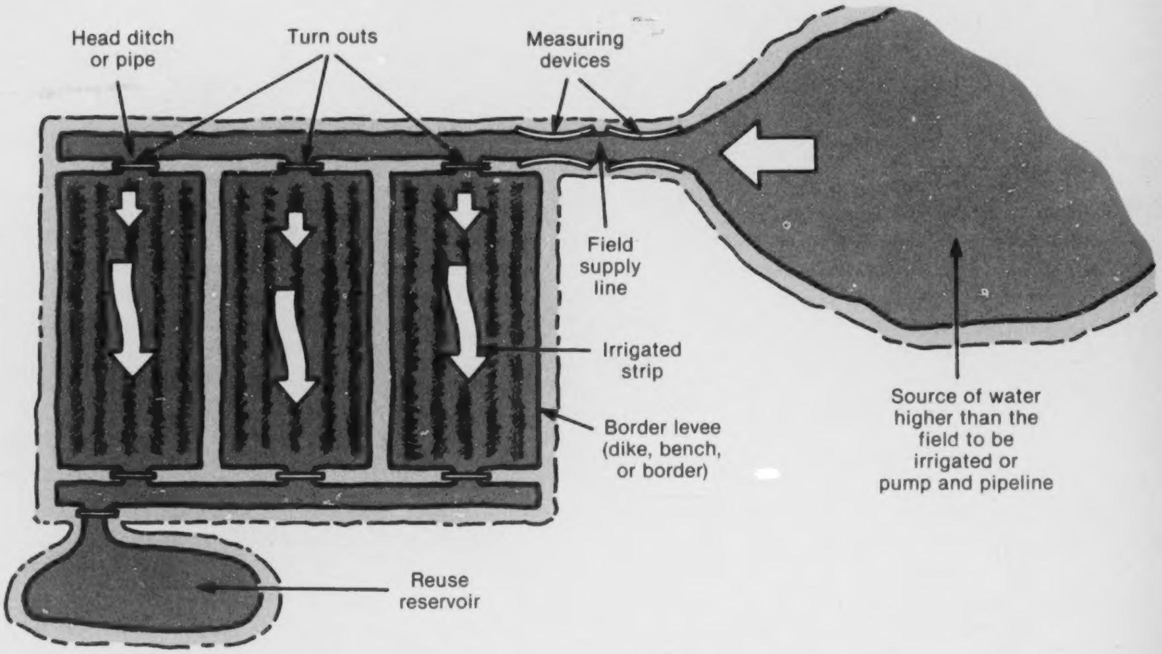
1. Delivery system:
    - Inadequate water-measurement devices
    - Unlined ditches
    - Improper location or alinement of ditches
    - Obsolete systems
    - Inflexible delivery schedule
2. Field application system:
    - Improper land shaping
    - Improper relationships of slopes, length of run, border widths, discharge rates
    - Improper design of sprinkler or drip system (pumping capacity, pressure, nozzle sizes)
    - Method of application not suited to soils or slopes
3. Ineffective water management:
    - Improper timing of irrigations
    - Incorrect application amounts
    - Improper scheduling of water
    - Excessive use of inexpensive water to save labor cost

SOURCE: U S. Interagency Task Force, *Irrigation Water use and Management*, USDI, USDA, EPA (Washington, D.C.: U.S. Government Printing Office, 1979).

In recent years, several developments have occurred that may further improve onfarm efficiency of surface systems. Mathematical models have been developed to simulate and predict interactions between soil, water, and crops during irrigation (18). These models may help decrease the random nature of surface irrigation design and operation and allow for more effective and timely water application. At present, models require further refinement before they are used widely because of the extensive variability in site conditions across the arid and semiarid region (e.g., soild infiltration rates, weather, and crop consideration).

Another important modification to surface irrigation has been use of a tailwater-reuse system, which consists of a reservoir at the lower side of a field to collect excess irrigation water. A pump then delivers recovered water back to a field. Tailwater-reuse systems allow application of large quantities of irrigation water (with accompanying runoff), reduce de-

Figure 54.—Surface-Irrigation System


Head ditch or pipe
Turn outs
Measuring devices
Field supply line
Irrigated strip
Border levee (dike, bench, or border)
Source of water higher than the field to be irrigated or pump and pipeline
Reuse reservoir

SOURCE: J. Howard Turner and Carl L. Anderson, *Planning for an Irrigation System* (Athens, Ga.: American Association for Vocational Instructional Materials, 1980).

Photo credit: USDA-Soil Conservation Service

Potatoes grow in furrow irrigation rows

mand for energy because pumping lift is less from a tailwater reservoir than from deep wells, and prevent damage to adjacent property by irrigation tailwater. However, irrigators who use a tailwater system lose land from crop production, and water that has been pumped through the system two or more times is lower in quality than the first time through the field.

Laser-controlled land leveling has increased the size of fields that can be irrigated using basin irrigation (a type of system consisting of a level area enclosed by earthen border ridges). Where soils are uniform, the combination of large flows with precision leveling can boost application efficiencies. Expansion of level basin irrigation over extensive areas of the

West is limited, however, by the availability of high-volume, instantaneous water flows and by potential problems with surface drainage in areas with substantial rainfall. The disadvantages associated with land leveling are a problem also.

Sprinkler Irrigation

Sprinkler irrigation is the application of water to the soil surface in the form of a spray, somewhat as rain. Many different types of sprinkler systems exist; in the United States, center-pivot systems represent the major sprinkler irrigation method (fig. 55).

With proper design and under correct management, sprinkler irrigation systems have a minimal amount of deep percolation and runoff loss. The primary practices available to an irrigator to minimize these losses further are design changes or changes in operating procedures. For example, sprinkler spacings, operating pressures, and set times may be changed, or additional use of automated equipment to control the system may be employed.

Energy conservation has received considerable attention in recent years and poses a special problem in continuously moving systems (center-pivot or lateral move). Reducing pressure while saving energy tends to lower irrigation efficiency because more water is applied and more runoff occurs. Modified-tillage practices, for example, basin tillage, can be incorporated into the farming program to reduce these runoff losses. Another practice is the placement of water application devices below the crop canopy. Low-energy precision application systems apply water directly to the irrigation furrow at low pressure through drop tubes as the sprinkler continuously moves through the field. Thus, runoff and spray evaporation are minimized (20).

Drip Irrigation

Drip, or microirrigation, is the frequent, slow application of water to the soil near the roots of a plant in sufficient amounts to meet its needs (fig. 56). The technology was introduced in the Western United States in the early 1970's; since then, its use has expanded to approximately 494,000 acres in 1980 (16). Drip irrigation is used primarily on high-value crops such as avocados, citrus fruits, strawberries, tomatoes, vineyards, and deciduous orchards, but has also been adapted to other types of crop production. Among the advantages of its use are:

- enhanced water control;
- lower seedling mortality;
- greater uniformity of plants, bushes, or trees;
- fuel savings;
- increased flexibility in the use of fertilizers;
- fewer weed problems;
- overall yield increases; and
- erosion control.

In theory, drip irrigation can increase irrigation efficiencies by reducing evaporation and deep percolation losses because a small amount of water is applied to a small portion of the soil surface. Actual water savings with a drip irrigation system, when compared to conventional surface or sprinkler irrigation, depends on such factors as irrigation frequency and crop.* In irrigation of row crops or crops with a nearly full cover, the water savings from reduced evaporation may be less. Drip irrigation with microsprinklers** may increase evaporation losses when compared with conventional drip systems because more of the surface is wetted.

Although the high irrigation efficiency associated with drip irrigation makes its use attractive, drip irrigation has some physical and economic limitations. Beyond the wetted zone, soil salinity may increase. Also, in most systems only a small portion of the soil is wet and plant roots tend to be confined to this area. If water delivery is stopped suddenly, severe plant stress can occur quickly. Large capital investments are required for plastic pipe, filtration

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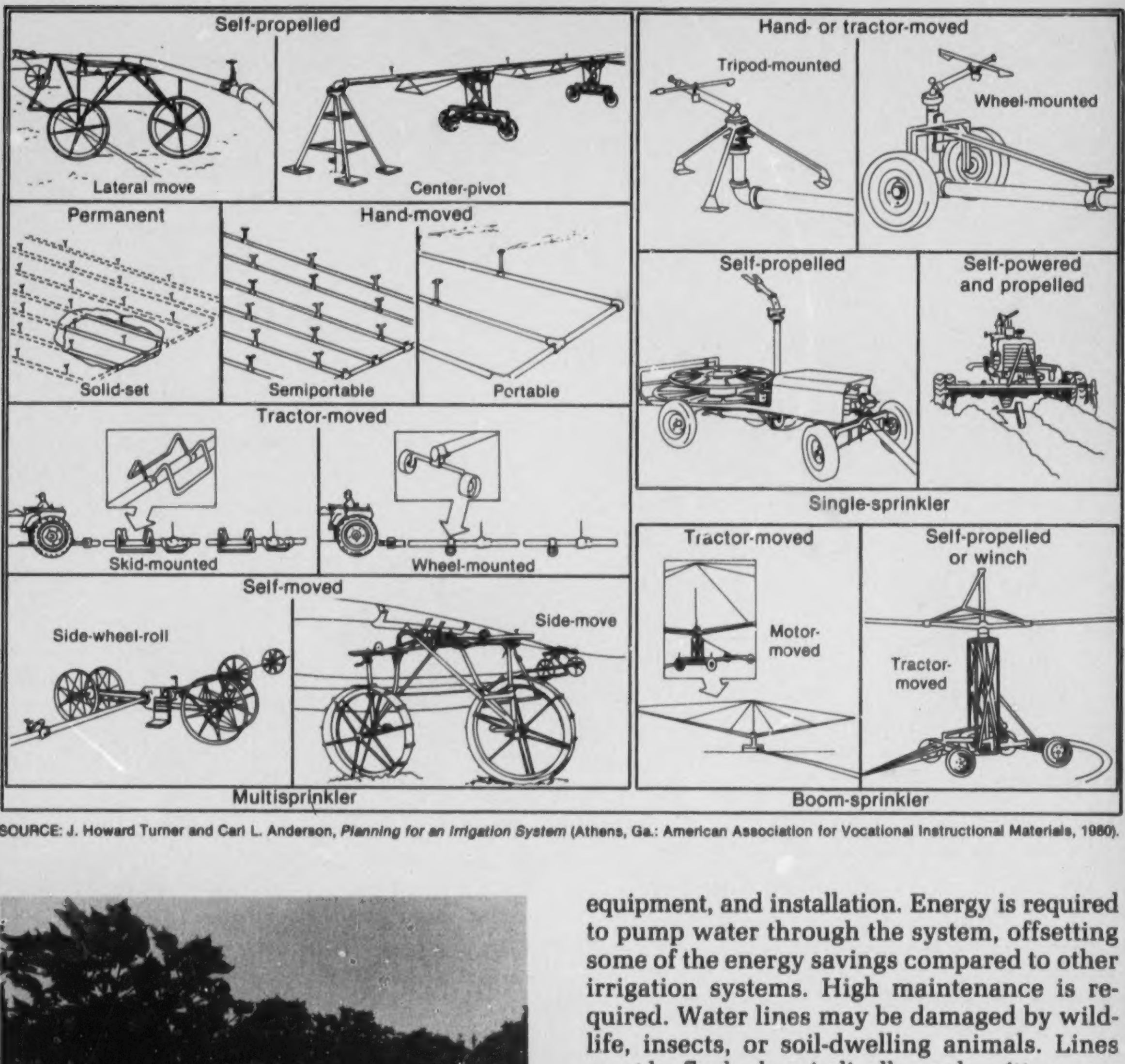
*The most favorable situation occurs with orchard crops in early growth stages where large areas of the surface is exposed and water is not needed in areas not yet explored by roots.

**Microsprinklers are smaller than conventional sprinkler heads but larger than standard drip emitters. Their use helps alleviate clogging hazards associated with emitters and have been tested in orchards to apply greater amounts of water than would be possible under conventional drip irrigation.

Figure 55.—Sprinkler Irrigation System


Self-propelled
Lateral move
Center-pivot
Permanent
Solid-set
Hand-moved
Semiportable
Portable
Tractor-moved
Skid-mounted
Wheel-mounted
Self-moved
Side-wheel-roll
Side-move
Multisprinkler
Hand- or tractor-moved
Tripod-mounted
Wheel-mounted
Self-propelled
Self-powered and propelled
Single-sprinkler
Tractor-moved
Motor-moved
Self-propelled or winch
Tractor-moved
Boom-sprinkler

SOURCE: J. Howard Turner and Carl L. Anderson, *Planning for an Irrigation System* (Athens, Ga.: American Association for Vocational Instructional Materials, 1980).

Photo credit: USDA-Soil Conservation Service

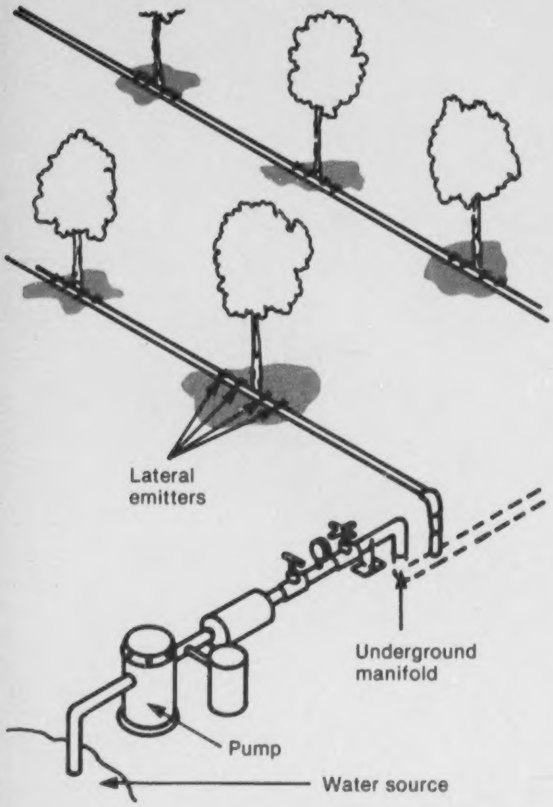
In a test field in California, private researchers are experimenting with the use of drip irrigation on furrowed cotton

equipment, and installation. Energy is required to pump water through the system, offsetting some of the energy savings compared to other irrigation systems. High maintenance is required. Water lines may be damaged by wildlife, insects, or soil-dwelling animals. Lines must be flushed periodically, and emitters may clog because of chemical buildup, silt, sludge, algae, slime, or roots. Emitters must be inspected frequently, and breakdowns in the system are sometimes not seen, especially where buried drip lines are used.

Subsurface Irrigation

Subsurface irrigation is accomplished by artificially raising the water table close to the soil

Figure 56.—Drip Irrigation Systems



Drip irrigation systems usually consist of a network of small-diameter plastic tubing along each row or between pairs of crop rows. Water is discharged through uniformly spaced small openings in the tubing or through emitters, nozzle-like devices that regulate water flow from lateral lines into the soil. Filtration equipment, provisions for fertilizer and pesticide injection, a fertilizer holding tank, and hardware to regulate water pressure are usually included as part of the system.

SOURCE: J. Howard Turner and Carl L. Anderson, *Planning for an Irrigation System* (Athens, Ga.: American Association for Vocational Instructional Materials, 1980).

surface. Water reaches the plant roots through capillary movement upward.

The advantages of subsurface irrigation include reduced evaporation, erosion control, and fuel and fertilizer savings. This method of irrigation also allows cultivation and other surface operations to be carried on without concern for the irrigation period.

Certain physical conditions must be met to ensure the success of subsurface irrigation, and these limit its application. First, soils should permit rapid lateral and downward movement of water yet should be capable of lifting the moisture from the water table throughout a major portion of the root zone. Second, the topography of the land should be smooth, uniform, and approximately parallel to the water table to allow for even irrigation. Third, salinity control is necessary and often requires the use of auxiliary irrigation systems (surface or sprinkler) to leach salt that accumulates at the soil surface as water evaporates. Auxiliary irrigations may also be needed for seed germination and plant establishment.

Limited Use of Supplemental Water

INTRODUCTION

In recent years, in areas where water supplies have become scarce or where the price of water has increased, two concepts of irrigation management, distinct from full irrigation, have evolved. "Supplemental" irrigation manages precipitation and irrigation water together to supply full-crop water needs. In "deficit" irrigation, applied water or applied water combined with precipitation is less than the amount of water needed for maximum crop yield.

For limited irrigation to succeed, a management strategy is necessary that integrates crop selection, soil manipulation, and irrigation system management with available water and economic conditions. This plan is flexible and varies from year to year.

Crop Considerations

Limited irrigation normally requires a diversified cropping program. This program includes:

- relatively drought-resistant crops;
- deep-rooted crops or crops with dense root systems that can tap soil water or enhance infiltration;
- crop rotations to ensure that water is available during growth periods that are sensitive to water stress; and
- in areas of summer precipitation, cropping patterns that provide for a fallow period when rainfall can be stored.

Soil-Water Considerations

Tillage practices, water-storage facilities (e.g., tanks and ponds), and soil-water monitoring are key elements in limited irrigation. As discussed earlier in this chapter, many land-forming techniques can be used to improve infiltration and ensure that precipitation and irrigation water are retained onsite.

Auxiliary water-storage facilities can also be used to capture runoff for later use. Water can be pumped from the storage facility when crops need to be irrigated or when the soil can retain the water.

Another aspect of soil-water management is monitoring the extent of soil-water deficit. This practice can help a grower identify when irrigation is required.

Irrigation System Management

Effective limited irrigation requires that recoverable losses (e.g., deep percolation and runoff) are minimized and that water is available to the crop during critical growth periods. Recoverable water losses can be reduced by increasing onfarm distribution and application efficiencies (see previous discussion under full irrigation).

Application methods, suited to the irrigation system, can also be manipulated to distribute limited water over a greater land area. For surface irrigation systems, for example, these methods could include alternate furrow irrigation, which tends to reduce deep percolation and results in greater lateral movement of applied water in the soil, and alternate furrow irrigation plus basin tillage. This latter practice allows rainfall to be captured while irrigation is proceeding. With both spinkler and surface methods, irrigators could practice skip-row planting which leaves a number of rows fallow to serve as a reservoir for soil water.

A second management practice for use in deficit irrigation is a limited irrigation-dryland system. In this system, a field is divided into three water-management sections. The upper half of the field is managed as fully irrigated. The next one-fourth is managed as a "tailwater runoff" section that uses runoff from the fully irrigated section. The lower one-fourth is managed as a dryland section. This system has been tested in the semiarid Texas High Plains region; limited research indicates that it has high irrigation water-use efficiency when compared to conventional irrigation (29).

Finally, the timing of irrigation water application is important. This requires that a knowledge of a crop's most sensitive growth period. If critical growth periods are known, irrigation water can be applied at that time to as large an area as possible. The irrigation is then terminated when plant-water stress on remaining unirrigated areas reaches a critical point and when the probable economic response to additional applied water would be mininal for the area already irrigated. A second irrigation begins on the area first irrigated and is normally continued until the economic contribution from irrigation declines or the crop reaches maturity (2).

ASSESSMENT

Limited irrigation has wide geographic potential. It could be applied in those irrigated areas where rainfall can supplement irrigation water or where drought-resistant crops are available. Currently, most limited irrigation is practiced in the southern Great Plains where high costs for pumping irrigation water are encouraging many farmers to shift from full irrigation to dryland farming. For these individuals, limited irrigation is one way to maintain higher crop production than possible with dryland farming while minimizing irrigation costs.

Economic and institutional considerations currently restrict extensive applications of limited irrigation to areas that face severe water shortages. Management requirements are high, and crop yields may decline when compared to a fully irrigated situation. Limited irrigation also requires precise and timely application of water; least expensive irrigation methods (e.g., surface irrigation) are often not suitable. The availability of large irrigation flows may limit the use of surface irrigation. Computerized instrumentation may be needed to monitor soil and crop and weather conditions and to control irrigation equipment. Institutionally, because this is a relatively recent development in irrigation-system management, many irrigation-system designers and extension personnel may not be able to provide appropriate information to producers who wish to change to a limited system.

Application of deficit irrigation is limited also by several technical considerations. First, standard procedures presently used to predict seasonal crop-water requirements and critical, water-sensitive growth periods (water production functions) are not accurate for more than one geographic area or crop, thus, results cannot be extrapolated across broad geographic areas or even from one field to another. Second, unless actual evapotranspiration and predicted evapotranspiration deficits are monitored closely and precisely, it is difficult for a producer to plan irrigation applications during water-stress periods. Monitoring programs are costly, however, and beyond the means of many individuals.

CONCLUSIONS

Many opportunities for improving soil-moisture conditions exist, both where precipitation is used to supply crop-water needs and where irrigation is practiced. Some of these technologies have been adopted by producers, but numerous barriers remain to their widespread application. First, many of these practices are effective under certain soil and/or climatic conditions. Where site conditions are not appropriate, application can yield little or no improvement in soil-water conditions. Second, some practices require large economic investments for equipment, fuel, and labor; application costs may outweigh their benefits in terms of higher farm or ranch profits. Third, the use of some technologies is hindered by Federal and State institutions. For example, mechanical land treatments on public rangelands by individuals are often prohibited; water saved by irrigators is often not available again for their use. Finally, some practices are difficult to incorporate into existing farm and ranch operations and may require new equipment or skills.

The extent of soil-water increase that can be expected with the adoption of a particular technology is difficult to quantify, given the wide variability in site conditions across the arid and semiarid region. For technologies that are used on irrigated land, data that assess the effects of widespread adoption on total water supplies are lacking. Similarly, information on economic and social consequences of adoption is generally not available.

Finally, soil salinization on irrigated lands and its associated effects on other natural resources may result in a reappraisal of the potential for dryland and rangeland agriculture in the Western United States. If a shift to limited irrigation or dryland or rangeland agriculture does occur, it may present Western agriulture with some new opportunities for production.

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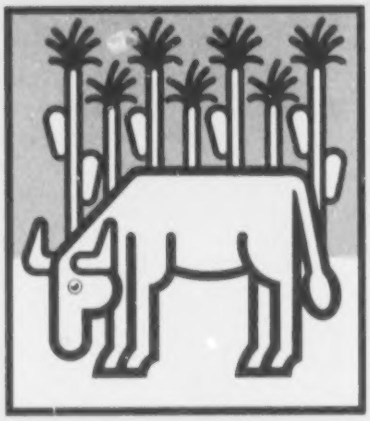

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Chapter IX

Technologies Affecting Water-Use Efficiency of Plants and Animals

In the past, agricultural scientists and producers in the United States often chose agricultural technologies for their contribution to high productivity. Essentially, these practices made the natural environment less hostile for plants and animals, a change from depending on native organisms that were closely adapted to sometimes harsh conditions. Today, as natural resources become more limited and economic costs increase, biological technologies that use existing natural resources more efficiently are needed. In the arid and semiarid areas of the West, these practices would be water-sparing and would use the special features of the region.

This chapter focuses on technologies that "stretch" the amount of plant or animal produced per unit of water used. As such, these technologies are well-suited to the arid/semiarid region. The emphasis here is on working within the natural limits of arid and semiarid lands with sophisticated technologies to provide an array of opportunities for sustainable agriculture.

Regardless of the quantity of water available for irrigation agriculture, it is likely that these technologies will figure more prominently in the region's future. If the amount of water available for Western irrigation is maintained, these technologies can add diversity to agricultural production in the region. If, however, expectations of less irrigation water are realized, these technologies may be vital in easing the transition to more suitable production systems. In dryland and rangeland agriculture, where production is usually limited by water, these practices can help sustain some current styles of production.

THE WATER SETTING

Water—the principal ingredient in living tissue—plays a vital role in biochemical reactions, maintains cell rigidity, moves materials within plants and animals, and helps to heat and cool them. Water continuously flows through most organisms and a certain quantity is an absolute necessity. When plants open pores (stomata) in their leaves to take in carbon dioxide for photosynthesis, water is lost by transpiration, a process significant because it is both essential and considerable. Desert plants may consume 100 times their weight in water each day even though they physiologically require only about 10 percent of that amount. While some plants are able to slow transpiration, it cannot be stopped completely without also stopping all plant growth.

Because of the large amounts of water they use, plants are a major component of the hydrologic cycle, and technologies have been developed to make hydrologic changes by modifying vegetation (see chs. VI, VII, and XI). Because animals use much smaller amounts of water they are not usually considered to be part of the hydrologic cycle. Both animals and plants, however, are vital to agriculture. In arid and semiarid lands, where water often determines survival and production, the efficiency with which organisms use water has important implications for sustaining all types of agriculture.

Plants have evolved a number of different ways of coping with water shortages. They may almost totally escape drought by germinating, growing, and reproducing before water becomes limited or only after a heavy rainfall. They may "resist" drought with special anatomical and physiological mechanisms to take up, store, and retain water. Or they may "tolerate" drought with mechanisms to limit the destructiveness of internal water deficits.

The relationship between plant growth and water stress is complex. A number of different drought-resisting mechanisms may come into play during a plant's life, and its sensitivity to water stress may vary with each. The different mechanisms may involve disadvantages as well as advantages. For example, a crop variety with a short growing season may mature before drought occurs, but in rainy years its yields are likely to be less than that of a long-season variety. This complexity has slowed the development of drought-resistant agricultural plants.

Animals exhibit a similar range of adaptations to limited water supplies. Some, such as kangaroo rats, may never drink water, obtaining moisture instead from their diet or even from dew, and excreting little water.

In order to be meaningful, comparisons of these and other differences in water use must include both the amount of crop, forage, or animal produced and the amount of water used. The concept of water-use efficiency (WUE) allows this comparison. As a general measure of efficiency, this term applies equally well to plants and animals, but it is seldom applied to animals because their relative water use is small.

Plant Water-Use Efficiency

For plants, biological WUE is defined as the total dry weight of plant material produced per total water lost by transpiration. Agronomists often use a different definition of WUE known as "agronomic WUE," which is the amount of harvestable or economic biomass produced per water lost by transpiration and evaporation. These two definitions allow distinctions to be made between inherent biological processes and the processes and conditions that apply to plants grown as crops (19).

Instantaneous measures of WUE are not meaningful, since plants constantly adjust water use to changing environmental conditions. Over the entire season, however, biological WUE is relatively constant for a given species. Variations are common among species (table 57); these differences relate to time of year that plants grow, evolutionary history, and plant physiology. For example, grasses as a group tend to use water more efficiently than shrubs (27). But individual species of drought-adapted shrubs may use water more efficiently than some grass species.

Attempts to increase WUE by altering either photosynthesis or transpiration have usually failed. For instance, antitranspirants, chemicals that reduce transpiration, have been investigated extensively but have not been widely used (14). While they can decrease transpiration effectively, they do not increase WUE because they also reduce photosynthesis and thus plant growth. There may be site-specific circumstances in which this is not a disadvantage, such as in the control of plants along streams.

Table 57.—Comparison of the Total Amount of Biomass Produced per Total Amount of Water Used in Transpiration for Crop Plants

Biological water-use efficiency has been divided by potential evapotranspiration in order to correct for climatic differences.

Crop	Biological water-use efficiency with climatic correction (kg/ha/da)[a]	Photosynthetic type
Alfalfa . . .	63, 90	C_3
Oats	90	C_3
Soybean .	102	C_3
Potato . . .	106	C_3
Barley . . .	106	C_3
Wheat . . .	112	C_3
Corn	151,213	C_4
Sorghum .	200,240	C_4
Millet	198,260	C_4

[a] Kilograms/hectare/day.

SOURCE: Wayne R. Jordan, Ronald J. Newton, and D. W. Rains, "Biological Water Use Efficiency in Dryland Agriculture," OTA commissioned paper, 1982), table 1A; Original sources: L. J. Briggs and H. L. Shantz, "The Water Requirement of Plants. II. A Review of the Literature," U.S. Department of Agriculture, Bureau of Plant Industry Bulletin 285, 1913; C. B. Tanner, and T. R. Sinclair, "Efficient Water Use in Crop Production, H. M. Taylor, W. R. Jordan, and T. R. Sinclair (eds.) (Madison, Wis.: American Society of Agronomy, 1983); H. L. Shantz and L. N. Piemeisel, "The Water Requirement of Plants at Akron, Colorado," *Journal of Agricultural Research* 34:1093-1190, 1927; R. J. Hanks, "Yield and Water Use Relationships: An Overview," *Limitations to Efficient Water Use in Crop Production*, H. M. Taylor, W. R. Jordan, and T. R. Sinclair (eds.) (Madison, Wis.: American Society of Agronomy, 1983).

Water-use improvements in the past have often resulted from increases in agronomic WUE because of the flexibility plants show in allocating resources into different plant parts. For example, tepary beans respond to overirrigation by producing leaves instead of seeds. While biological WUE remains unaffected, agronomic WUE is decreased. Since beans are the desired product, a knowledge of agronomic WUE is more important to crop management and breeding. Also, crops can be managed to minimize soil evaporation or to change crop maturity to shift yields to before or after drought occurs. Both changes can increase agronomic WUE.

Animal Water Use

Significant differences exist in the amount of water required by different livestock and wildlife species (table 58). Some animals require large amounts of freshwater for drinking. Others require little drinking water, since they can reduce water requirements when it is limited, conserve available water, or acquire most of their needs from food. A list of animals, in order of increasing adaptation to drought would be water buffalo, European cattle, African (zebu) cattle, wool sheep, hair sheep, goats, and camels (28). Water use also will vary depending on the nature of the forage and weather conditions.

Because animals use comparatively little water, there has been little effort to use or breed animals that use less water. Instead, efforts have concentrated on ways to increase the efficiency with which animals convert plant biomass into their own. As long as water use remains unaffected, this process improves animal WUE.

Biological v. economic (agronomic) yield also applies to herds and single animals. Maintenance costs, in terms of water and food, are substantial for many single animals. In some cases breeding populations are maintained from year to year and their requirements must be counted in total water- and forage-use effi-

Box T.—Three Carbons, Four Carbons, and Cam: Plant Physiology and Water Use

Plant biological WUE falls into three broad categories corresponding to differences in photosynthesis: CAM, C_4, and C_3 types. These processes, by which sunlight is converted into organic matter, are different enough to affect many features. CAM, or crassulacean acid metabolism, plants use water most frugally. Stomata open at night when evaporative demand of the air is low but, if water is plentiful, many CAM plants also take up carbon dioxide during the day, and water use increases dramatically. Maximum growth rates of CAM plants such as cacti are low because of very low photosynthetic rates. Pineapple, the only agricultural CAM plant, is more productive than most. A large number of food and forage plants use four-carbon, or C_4, physiology and have intermediate biological WUE—e.g., corn, sorghum, grain amaranth, and many warm-season range grasses. They have high photosynthetic rates and accumulate dry matter quickly. Most of the cereal grains, almost all woody trees, many vegetables, and cool-season range grasses belong to the the three-carbon, or C_3, group. This group has the lowest biological water-use efficiency and also is least effective in retaining the carbon absorbed.

These fundamental physiological differences have not been exploited agronomically yet. Few CAM species are of economic value now, but they may have potential for specific, high-value products. While four-carbon species are efficient water users, they also grow best during hot summers and therefore consume large amounts of water over the total season. These species are generally sensitive to low temperatures, so they cannot be planted earlier or later to reduce summertime water demands. Attempts to breed hybrids with the best features of each type have so far failed.

SOURCES: James R. Ehleringer, "Photosynthesis and Photorespiration: Biochemistry, Physiology and Ecological Implications," *Hortscience* 14(3):217-222, 1979; James R. Gilley and Elias Fereres-Casteil, "Efficient Use of Water on the Farm," OTA commissioned paper, 1982; Wayne R. Jordan, Ronald J. Newton and D. W. Rains, "Biological Water Use Efficiency in Dryland Agriculture," OTA commissioned paper, 1982.

Table 58.—Co[illegible]tive Water Use Of Animals

Low daily water turnovers reflect a high water-use efficiency. Thus, the animals listed first use the least water.

Animal	Body weight (kg)	Daily water turnover (ml/kg$^{0.82}$)	Environment
Antelope:			
Oryx	136	70	African grassland
Wildebeest	175	137	African grassland
Kongoni	88	116	African grassland
Eland	247	213	African grassland
Goat:			
Somali	40	185	African desert
Camel:			
Somali	520	188	African desert
Sheep:			
Dorper	42	170	African grassland
Merino	38	180	African grassland
Ogaden	31	197	African desert
Karakul	31	205	African grassland
Cattle:			
Boran	417	224	African grassland
Boran	197	347	African desert

SOURCE: L. A. Stoddart, A. D. Smith, and T. W. Box, *Range Management* (New York: McGraw-Hill Book Co., 1975), p. 318. (Original source: MacFarlane, "Prospects for New Animal Industries: Functions of Mammals in the Arid Zone," *Proceedings of the South Australian Water Research Foundation* (Adelaide, S. Australia, 1972).)

ciency of the herd. Of the animals slaughtered, only a portion is economic yield. About 50 percent of an animal is used for meat, while byproducts of various kinds account for another 15 to 20 percent. Like plants, animals have been selected for "agronomic" efficiency: faster and greater weight gains in marketable products per total nutrients spent for animal maintenance.

THE TECHNOLOGIES

Methods of Improving Plants and Animals

Biotechnologies

INTRODUCTION

The term "biotechnology" has come to represent a cluster of methods for introducing and reproducing new genetic variation in bacteria, plants, and animals as well as a number of industrial applications of biological processes. In this section, only those technologies are considered that may increase the WUE of agricultural plants. The application of similar technologies to animals is discussed under "Animal Breeding."

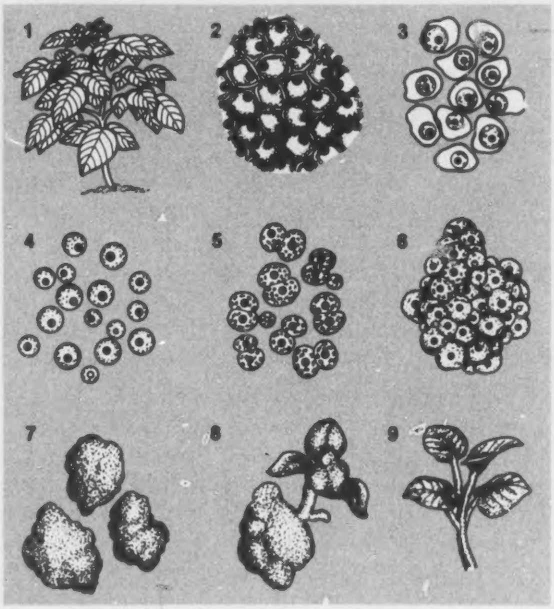
The promising technologies include tissue culture and other techniques for propagating organisms; fusion of plant cells (protoplasts) either within or between species; and precise recombinations of DNA, the genetic material (figs. 57 and 58). These methods usually involve intensive laboratory treatment and may be used alone, in conjunction with one another, or with more conventional breeding methods.

ASSESSMENT

The application of various kinds of biotechnology to the specific problems of water use in arid and semiarid lands involves manipulation of the mechanisms that influence the uptake, use, and loss of water by organisms. For example, some experts speculate that the drought tolerance present in some Western weeds could be added to unrelated crops. Or perhaps cell lines selected for salt tolerance could produce crops for irrigated areas with salt accumulation.

Figure 57.—Working With Protoplasts

"Clones" of a parent plant can be regenerated from its isolated protoplasts by the methods developed for culturing tissues as shown here. Protoplast fusion involves an additional step: protoplasts of two genetically unlike parents would be combined at step 4. The offspring are not like either parent; they often contain unique combinations of genetic material that could not be produced with conventional plant-breeding methods.



Small terminal leaves are first removed from a young potato plant (1). The leaves are placed in a solution containing a combination of enzymes capable of dissolving the cell wall (2). Another substance in the solution causes the protoplasts to withdraw from the cell wall and to become spherical, thereby protecting the living protoplasm during the disintegration of the wall (3). The isolated protoplants are next transferred to a culture medium (4), where they grow, synthesize new cell walls and begin to divide (5). After about 2 weeks of culture each protoplant has given rise to a clump of modifier-estimated cells, called a microcallus (6). The microcalluses are transferred to a second culture medium, where they develop into full-size calluses (7). At this stage the cells of the callus begin to differentiate, forming a primordial shoot (8). The shoot develops into a small plant with roots in a third culture medium and is then planted in soil (9).

SOURCE: James F. Shepard, "The Regeneration of Potato Plants From Leaf-Cell Protoplasts," *Scientific American* 246:156, May 1982.

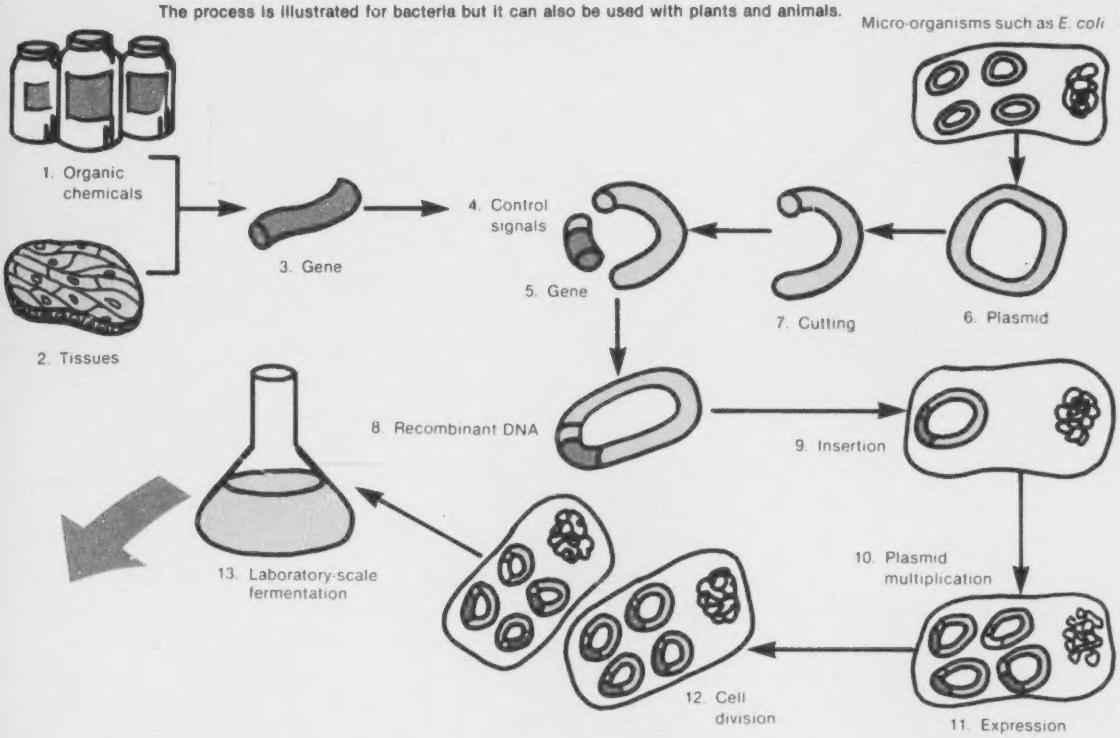
Some of these technologies are rapidly entering agriculture. Tissue culture is already in commercial use and, in the next 10 to 15 years, is likely to make important contributions (23). Other biotechnologies face a potentially long period of basic research before their applications will be available. Protoplast fusion, like other more complex techniques, cannot be used now with much expectation that the desired results will occur. Recombinant DNA technology holds the most promise for precisely changing plant features, but it is farthest away from wide-scale development. Few practical applications of these technologies are expected within the next decade.

Institutional constraints exist in addition to the technical ones. There is concern, for example, that reliance on laboratory practices might narrow the genetic diversity of present crops to an undesirable degree. On the other hand, some believe that human-induced variation and the germplasm banks that might spring up could actually increase genetic diversity. Other concerns regarding the release of novel and potentially dangerous organisms into the environment have diminished. For example, experience has shown that safeguards are generally adequate to contain potentially troublesome organisms used in industry.

These technologies have already had an important effect on the way agricultural research is conducted. Some private universities and corporations are involved in agriculture for the first time. Few of these leading research institutions are also involved directly in arid land studies. Furthermore, rapid industrial expansion has created at least a short-term shortage of trained personnel. As scientists and technicians move rapidly into the private sector, universities are concerned that their ability to conduct basic research and to train new teachers will be jeopardized. It is not clear to what extent the large involvement by profitmaking corporations may shape research priorities. If public sector research—e.g., at land grant universities, USDA laboratories, and State agricultural experiment stations—does not keep pace, there may be little progress in the application of new biological technology to problems of social importance that have little foreseeable profit. Also, since new life forms can be patented, there is concern that limited access to the results of private research may further limit public work.

Figure 58.—The Technique of Recombinant DNA Technology

The process is illustrated for bacteria but it can also be used with plants and animals.


Micro-organisms such as *E. coli*
1. Organic chemicals
2. Tissues
3. Gene
4. Control signals
5. Gene
6. Plasmid
7. Cutting
8. Recombinant DNA
9. Insertion
10. Plasmid multiplication
11. Expression
12. Cell division
13. Laboratory-scale fermentation

SOURCE: U.S. Congress, Office of Technology Assessment, *The Impacts of Applied Genetics* (Washington, D.C.: U.S. Government Printing Office, OTA-HR-132, 1981), p. 6; and Genentech, Inc.

No consensus exists on biotechnology's near-term potential in agriculture. While much former skepticism has been allayed, these are capital-intensive enterprises that are capturing large amounts of public research money at a time when funds are limited. Therefore, the fear exists that less glamorous technologies—e.g., new approaches to classical plant breeding—will be overlooked.

Tissue Culture

Tissue culture is basic to the use of the other biotechnologies discussed here and to making the results of such biotechnologies available to agricultural scientists. It is accomplished by several methods (fig 57). In its simplest form, individual sexual cells such as pollen grains and eggs are stored and grown in artificial nutrient media. More complex methods allow identical plants to be developed from pieces of the parent after they receive several hormone treatments. In another type of culture, the initial unspecialized tissue, or callus, developed from a plant cutting is agitated to separate the cells; a new plant then regenerates from each cell. This more productive method can also be used to expose genetic variation among the individual cells of a single parent plant. If environmental stress is applied then to the culture, the survivors can be regenerated. This method may have important applications for problems of water stress.

Many important crop and forage plants can be regenerated from cuttings with these technologies. Strawberries, asparagus, pineapple, coffee, and horticultural plants are mass produced this way. More recently, mass propagation of alfalfa, jojoba, and some grass species

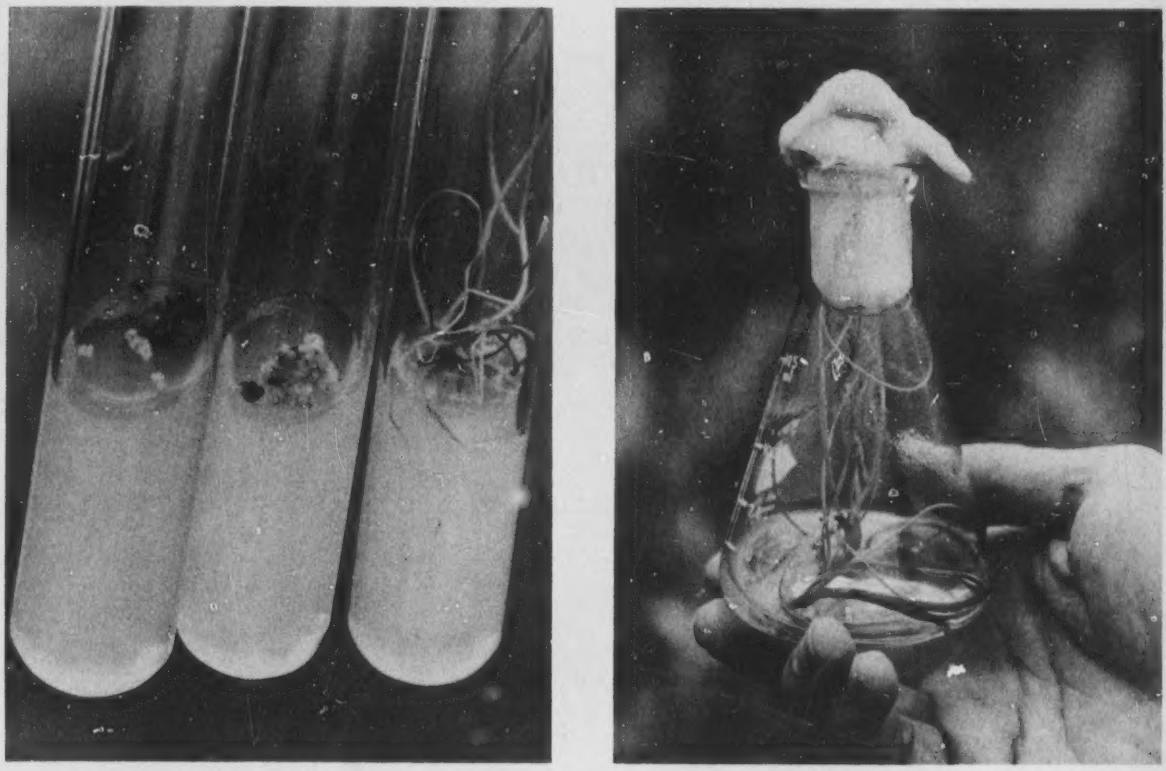


Photo credits: USDA-Agricultural Research Service

Wheat plants growing using tissue culture: white clump (left) are cells forming from live wheat anthers, masses of undifferentiated tissue grow from the cells (center test tube), in a special growing medium (right test tube and flask in right photo), a small plant develops from the cultured tissue.

has become possible. The savings in time and space can be substantial. For example, 25 gallons (about 100 liters) of Douglas fir cells in nutrient media can produce enough plants in 3 months to reforest about 120,000 acres of land (12).

When tissue culture techniques are used in conjunction with classical breeding methods, new germplasm can be made available rapidly, and the volume of material accumulated by difficult crosses can be increased quickly. For example, 65 new types of potatoes have been "cloned" from Russet Burbank cells and more than 134 virus-tree potato cultures have been developed.

A number of water-related stresses can be applied to plant-cell cultures, including salinity, drought, flooding, ion toxicities, nutrient deficiencies, and temperature extremes. Cell lines with resistance can be developed from the survivors. Recent experiments suggest that cell selection may provide researchers with material less susceptible to water stress (19). For example, alfalfa and rice cell lines have been obtained that tolerate 2 percent sodium chloride, a salt concentration lethal to nonselected cells. Gene dosage, or the number of duplicate sets of genetic material present within a given organism, can also be altered by treating cultured cells with chemicals. Varieties of rye differing only in gene dosage varied in susceptibility to cold and observations suggest that a similar relationship holds for susceptibility to water stress.

These treatments of plant cultures are recent, so it is difficult to evaluate their eventual impacts. Sodium chloride tolerance in cell lines, for example, is sometimes unstable and does not occur in later generations. In other cases, important water-related features characterize the whole plant but not isolated cells and tissues. Selection for these traits cannot be accomplished in cell culture.

Protoplast Fusion

If single plant cells in cultures are treated further to remove the tough cell wall, protoplasts remain. Protoplasts can then be combined, a crude way of creating new mixtures of genetic material that normally are prevented by natural breeding barriers (fig. 57). This method has been used with petunias, plants in the cabbage family, and tomato/potato pairs (pomatoes). Protoplasts from more distantly related species, such as tobacco and soybean, also have been induced to fuse. So far, it is possible to complete the necessary steps—strip the plant cell wall, alter the protoplast, regrow a cell wall, form a callus, and regenerate the plant—for only a few species. Until the fusion process is further refined, the features of the new plant will be unpredictable combinations of the parents.

This technique holds promise for creating unconventional hybrids before the more precise recombinant DNA technology is available. Combinations such as "pomatoes" do not have commercial value now, but investigators hope that closer crosses may. Wild relatives of crop plants often possess desirable features that adapt them to stress, but natural barriers exist to sexual crosses. For example, disease-resistant wild relatives often cannot breed with commercial potatoes. Protoplast fusion may be able to add this desirable genetic material to potatoes without breeding (25). The same process, or recombinant DNA techniques, may be applicable to the transfer of water-related characters such as changes in growth rate and production of "heat-shock" proteins (6).

Recombinant DNA

Recombinant DNA technology uses enzymes to break apart the genetic material (DNA molecules) in one organism and recombine it with

Photo credits: USDA-Soil Conservation Service

The grama grasses are important native Western forage plants. Biotechnologies such as tissue culture and conventional plant breeding are used for these types of plants as well as for the major annual crops

DNA pieces from another (fig. 58). The "recombined" material expresses new predetermined characteristics in the organism into which it is inserted. This process takes place in four stages:

1. Desirable genes are chosen and "vectors" are identified to carry them to the host.
2. The gene is prepared for splicing into the vector.
3. The vector is inserted and maintained in the host.
4. A number of hosts are cloned and the most desirable is selected for further modification or conventional breeding.

This methodology is far from routine for plants. The lack of vector systems and problems with regenerating whole plants have hindered progress. The genetic material of micro-organisms is simpler and transfers of DNA among bacteria or yeast are common. Therefore, near-term agricultural applications are likely to involve only microbes, either directly or as models for higher plants. For example, bacterial osmoregulation has been manipulated by moving the gene for proline production into nonproline-producing micro-organisms. The recipient bacterium increased its rate of nitrogen fixation while water stressed (21). Since osmoregulation is the process by which organisms control the uptake of water, it is crucial where water is limited.

Ultimately, all agriculture depends on carbon compounds "fixed" by plants from atmospheric carbon dioxide. Bacterial carbon dioxide fixation systems are considered to be models for plant systems, and preliminary studies suggest that bacterial systems can be altered by genetic manipulation (3). Attempts focus on reducing photorespiration of C_3 plants, the process by which about 40 percent of the energy acquired by plants is lost before organisms can use it.

Recombinant DNA techniques are often more difficult to use with plants than with bacteria and yeasts. In plants, the genetic material is confined within a nucleus, and there are few vectors for passing genetic material from the nucleus of one plant cell to another. The first genes were inserted across natural reproductive barriers between plant species in 1973, but the ability to transfer plant genes at will is some time away.

Because of these constraints the thrust of recombinant DNA work in plants is developing laboratory techniques and understanding basic plant physiology. Much of the success of past plant-breeding programs relied on the transfer of large segments of genetic material. A clear knowledge of the DNA-level changes was not necessary. Recombinant DNA work requires that the role of transferred genetic material be understood if it is to achieve its purpose and have successful agricultural applications. This is not possible now.

Classical Plant Breeding

INTRODUCTION

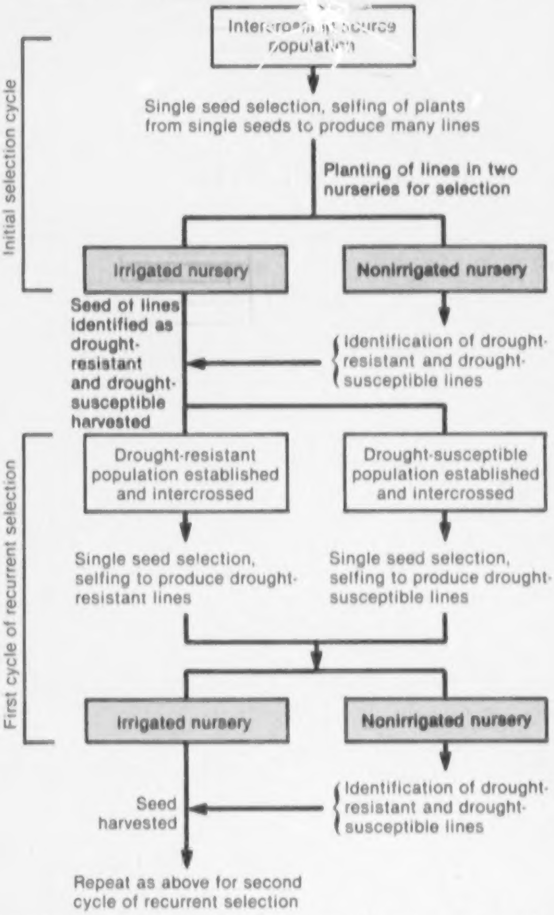
Plant breeders have traditionally worked with whole plants instead of the cells or molecules that characterize biotechnology. Plant breeding generally involves six steps:

1. choosing the crop for breeding,
2. identifying the breeding goal,
3. selecting methods to reach that goal,
4. exchanging genetic material among organisms,
5. evaluating the resulting offspring under field conditions, and
6. producing seed for distribution to producers.

Some technical parts of these steps have changed little over time: hand-pollination to cross similar plants, data collection from extensive field plots, and identification, by art as well as science, of the most promising young plants. New methods have changed other steps a great deal. Centralized research and seed production centers, single-crop specialists, collections of worldwide germplasm, and modern statistical evaluation have changed the face of contemporary plant breeding. The availability of genetic engineering technology promises to make even more changes.

The philosophical basis for crop-plant breeding, which is fundamentally important in the

Figure 59.—A Generalized Method for Developing Drought-Resistant and Drought-Susceptible Plants


Intercrossed source population
Single seed selection, selfing of plants from single seeds to produce many lines
Planting of lines in two nurseries for selection
Initial selection cycle
Irrigated nursery
Nonirrigated nursery
Seed of lines identified as drought-resistant and drought-susceptible harvested
Identification of drought-resistant and drought-susceptible lines
Drought-resistant population established and intercrossed
Drought-susceptible population established and intercrossed
Single seed selection, selfing to produce drought-resistant lines
Single seed selection, selfing to produce drought-susceptible lines
First cycle of recurrent selection
Irrigated nursery
Nonirrigated nursery
Seed harvested
Identification of drought-resistant and drought-susceptible lines
Repeat as above for second cycle of recurrent selection

SOURCE: A. D. Hanson and C. E. Nelson, "Water: Adaptation of Crops to Drought-prone Environments," *The Biology of Crop Productivity*, Peter S. Carlson (ed.) (New York: Academic Press, 1980), p. 97.

initial steps, may also be changing. For example, the ability to be productive under harsh environmental conditions, such as those imposed by drought, has not been a major breeding goal for most crop species. In fact, most plant breeding has involved selecting plants for superior yield in fertile environments or under other conditions of high external inputs (7). This approach assumes that plants which have high yields under irrigation or high fertilization will also have high yields when water- or nutrient-stressed. General plant adaptability is sought to a range of conditions. This is the most common approach to crop breeding and, for dryland crops, it has increased yields without affecting agronomic WUE (10). In some cases, this type of plant breeding has reduced genetic variability for those factors, such as nitrogen fixation, stress tolerance, and photosynthetic efficiency, that may be beneficial in arid and semiarid environments.

Another approach to plant breeding seeks, in the case of water shortages, to enhance drought resistance in a manner similar to that used successfully for disease and insect resistance (fig. 59). Key features that confer resistance are identified and incorporated into less adapted varieties. Plant selection and evaluation are carried out under the same water-limited conditions that the crops are expected to endure because:

> Breeding lines that use water efficiently in a dry environment may not do as well as other lines under more favorable water conditions. This is because tradeoffs exist regarding plant responses in different environments. Therefore selecting plants for wide adaptability may be selecting for mediocrity. As a result, the most promising route for plant improvement under drought stress probably involves selection under water-limiting conditions (17).

Breeding programs of this type are common for forage plants, but similar ones for annual crops constitute only a fraction of the total breeding effort. Because these programs are new, they have yet to demonstrate their superiority to the first, more traditional, approach. They have the potential, though, for making major contributions to agricultural production because of the large geographic areas devoted to production of forage plants and the major areas of cultivated cropland that are susceptible to environmental limitations (table 59).

ASSESSMENT

Plant breeding for annual crops in the United States has a long and productive history. Experts estimate that crop improvements have accounted for gains of 1 to 3 percent in yields per acre each year for corn, wheat, soybeans, cotton, and sorghum (19). Yield increases have

Table 59.—Percent of the United States With Soils Subject to Environmental Limitations

Environmental limitation	Area affected (%)
Drought	25.3
Shallowness	19.6
Cold	16.5
Wet	15.7
Alkaline salts	2.9
Saline or no soil	4.5
Other	3.4
None	12.1

SOURCE: J. S. Boyer, "Plant Productivity and Environment," *Science* 218:445, Oct. 29, 1982.

come from gradually altering combinations of traits.

These include modifications of the partitioning of plant substances among organs and compounds, changes in seed retention characters, and alterations in the timing of flowering and of seed formation. For example, economic yield is usually a fraction of total plant dry matter, including roots (table 60). The size of the fraction depends on the plant species, water supply, and management. A significant portion of the yield increases obtained by plant breeding have been based on increasing this fraction. In wheat, the proportion of harvestable grain has increased from 35 to 50 percent over the last 20 years (4). Selection pressure in other plants would result in similar increases up to the limits established by the anatomy of the crop. When these increases do not increase evaporation or transpiration, they result in higher agronomic WUE.

Table 60.—Proportion of Crop Dry Matter Produced That is a Harvestable Product

Plant breeding has successfully increased the proportion of plant-produced dry matter that is a harvestable product. The figures given below are for highly productive irrigated varieties.

Crop	Product	Proportion economic product (in percent)
Cotton	lint	8-12
Sunflower	seed	20-30
Bean	grain	25-35
Tomato	fruit	25-35
Soybean	grain	30-40
Sorghum	grain	30-40
Corn	grain	35-45
Sugarbeet	sugar	35-45
Wheat	grain	35-45
Rice	grain	40-50
Pineapple	fruit	50-60
Potato	tuber	55-65
Alfalfa	hay	40-80

SOURCE: Adapted from Wayne R. Jordan, Ronald J. Newton, and D. W. Rains, "Biological Water Use Efficiency in Dryland Agriculture," OTA commissioned paper, 1982, p. A7, table 3A.

Until recently, little research has been conducted on range plants, but work in Utah, Montana, and the SCS Plant Materials Centers on plants for mined land reclamation has vitalized range-plant breeding. Vigorous, palatable, quickly established hybrid grasses are now available. Perennial range-plant breeding differs from breeding annual crop plants in several ways: survival, as well as production, is important; only enough seeds are needed to ensure genetic mixing and reseeding; and storage reserves for the next season's growth cannot be shunted into production. These requirements make breeding more complex.

Identification of the character or characters to be modified is the single most critical step in plant improvement; it dictates both breeding and evaluation methodology. Once characters are identified, breeders have been successful because they make selections from vast numbers of plants. One breeding program that uses computer-assisted seeding and harvesting allows seven staff members to test 30,000 plots of plants in four locations (29). Large selections may be important, especially for breeding drought resistance, since it probably involves many genes with small, difficult to measure, effects.

In many cases, the fundamental mechanisms of adaptation to water stress are not known. Where critical features can be identified for breeding, they are not based on one or a few genes, unlike the many disease- and insect-resistance traits used successfully in past breeding programs. Instead, the complex physiological and biochemical features that enable a plant to tolerate water stress vary from species to species. The properties that enable one plant to survive in an arid region—e.g., a large root system—may make another susceptible to severe desication, or drying.

Under such conditions, accurate laboratory measurements of the actual physiological feature that confers drought resistance may require hours. Measurement technologies are too time-consuming for the large numbers of plants needed for mass evaluations. Therefore, direct plant breeding for the biological characters that determine drought resistance awaits development of better laboratory technology. This problem can be overcome by correlating these physiological features with ones more readily observed and measured. Such genetic markers are used to identify some genetic diseases in humans and in animal breeding programs.

With adoption of the 1970 Plant Variety Protection Act and its 1980 amendments, institutional constraints to the development of new plant varieties decreased. Private investment has increased, and several times as many cotton, wheat, corn, and soybean varieties are being produced as before its passage. Other concerns remain, however. The trend for small seed companies to be taken over by large ones concentrates economic power in fewer hands. There is concern that this may increase seed prices or hinder development of varieties that have fewer customers or require fewer of a company's other products—e.g., pesticides. Fears also exist that the new systems for patenting germplasm will decrease germplasm availability at a time when it is needed (5).

Animal Breeding

INTRODUCTION

Animal production is a major feature of Western agriculture. Large acreages in the West cannot be cultivated because of erosion hazards or other factors. For these lands, production of animal protein or other products by ruminants (goats, cattle, sheep, wildlife) is a beneficial use of unique resources. Also, large numbers of cattle are raised on Western feedlots. In both cases, animal breeding can increase productivity.

The major focus of most animal-breeding programs is increasing the amount of animal biomass produced per unit of land area or per amount of plant material consumed. This can be accomplished by increasing the number of young animals produced each year or by increasing the rate at which each offspring gains weight.

Some breeding programs are related specifically to conditions prevailing in arid and semiarid lands. For example, several new breeds have been established to achieve greater heat tolerance for Western rangelands. These have involved the introduction of African and Asian sheep and cattle germplasm into European stock, the common rangeland breeds. Santa Gertrudis, Beefmaster and Africander cattle, and Dorper sheep resulted from these crosses.

Standard animal-breeding technologies have been used to accomplish these goals: introduction of new breeds to create hybrids, intentional selection for high growth rates among pure breeds, and development of composite populations. A variety of more intensive technologies are also finding their way into the livestock industry.

ASSESSMENT

The productivity of ruminant farm animals has increased substantially during the past two decades. For example, selection for growth and carcass traits within beef cattle breeds has changed some traits by 2 to 3 percent every generation. Additional increases in productivity have been obtained by crossing several cattle breeds: calf weight was increased by 20 to 25 percent in a three-breed rotational breeding program. These programs have used European breeds such as the Simmental, Gelbviech, and Maine Angou, which are larger and later maturing. Other programs use Texas Longhorns to decrease calving difficulty, increase disease resistance, increase fertility, and adapt the animals to the harsh environmental conditions that often prevail on open rangelands.

More intensive technologies, first used by the dairy cattle industry, are being adopted for other animals. Artificial insemination has markedly increased milk production, and over 50 percent of dairy cattle are bred this way. Artificial insemination is used for only 3 percent of beef cattle, but recent treatments to synchronize ovulation promise to decrease labor requirements and make it more acceptable (20). For those 3 percent, though, artificial insemination has dramatically improved weight, quality and disease resistance.

Photo credit: USDA-Soil Conservation Service

Texas longhorns, after hundreds of years of years of fending for themselves on the arid and semiarid ranges of Mexico, became the foundation of the U.S. cattle industry. They were almost replaced by European cattle breeds in the 20th century but interest in these hardy animals is increasing now

These improvements are being enhanced by embryo transfer and storage, methods similar to those used for plant-tissue culture. In embryo transfer, genetically superior cows are treated with hormones and, as a result, produce 6 to 20 eggs instead of one. These eggs are removed, fertilized with semen from a genetically desirable bull, and transfered to surrogate mother cows. All of the calves will be related to the superior genetic parents but will also acquire the disease-resistance of the surrogate mother.

Some additional embryo manipulations are possible before transplantation. New genetic combinations can be made by combining two embryos, or one embryo can be divided to produce identical twins. All of these processes are complex and expensive. They require laboratory facilities, trained embryologists, and about $2,000 for each procedure. These techniques have developed in conjunction with embryo storage methods. It is now possible to freeze embryos, conserving important genetic resources on a worldwide basis. Frozen embryos are often used in embryo transfer, and new technologies promise to make both procedures less expensive and more widely available. For example, Rio Vista Farms in Texas have perfected a method of transferring frozen embryos in plastic straws filled with protective fluid. With these, thawing and implantation can be done by veterinarians or less specialized personnel.

Some of this technology is not equally available to ranches of different sizes and incomes. Smaller farms and ranches cannot usually manage the complicated rotational breeding programs that increase productivity. Since about 70 percent of the beef cattle in the United States are in herds of fewer than 100 animals, a large number of animals may be excluded. Composite populations of animals developed from a wide germplasm base selected from several breeds would make the advantages of hybrid vigor available to small cattle operators perhaps for the first time.

The cattle industry is in transition now, and changing economic conditions will affect the availability of credit and the location of livestock centers. Some people expect that the West will decline as a center for cattle feeding but retain its prominence in rangeland cow/calf operations (11). A continuing need will exist for animal germplasm suited for arid and semiarid rangelands, but declining markets for red meat may have unexpected effects on livestock producers.

Innovative Applications of the Technologies

"New Crops": Plants and Animals

> The greatest service which can be rendered any country is to add a useful plant to its culture . . . .
>
> Thomas Jefferson, 1821

INTRODUCTION

The domesticated plants and animals raised by American farmers and ranchers frequently change. Seventy years ago avocados were virtually unknown, soybeans were grown only in a few States, research on grain sorghum had barely begun, and European cattle were relative newcomers. Now each of these organisms is well established, filling demands for high-value or drought-adapted human and animal food.

Concern remains that other agricultural plants and animals are needed. These are:

- present agricultural organisms need diversification with new genetic material to prevent attack by new diseases and pests;

Box U.—Sunflowers: A Successful New Crop

Sunflowers are native American plants that, under some conditions, possess environmental and economic advantages over other crops in the northern Great Plains: they offer drought and flood resistance and tolerance for salinity and frost. Several North American Indian tribes used sunflowers extensively but large-scale commercial development of sunflowers occurred first in Europe. In 1964 the U.S.S.R. released the first high-oil variety, stimulating U.S. interest. Then, in the late 1960's, the sharp decline in Russian exports opened the European market to U.S. exporters. At the same time, several universities, USDA, and a commodity organization increased the agronomic and economic attractiveness of the crop. Since then, U.S. acreage has expanded 65 times to about 4 million acres. In North Dakota, South Dakota, and Minnesota, the major producing States, sunflowers have maintained their economic edge over other small grains, stood up to adverse weather conditions, and provided growers with an alternative crop. In 1980, a future's market was established, and other countries became eligible for financial assistance for U.S. sunflower purchases. While acreage continues to fluctuate, the future of sunflowers appears bright.

SOURCES: Gary L. Laidig and J. W. Twigg, "Historical Crop Studies," *Feasibility of Introducing New Crops: Production, Marketing, Consumption (PMC) Systems*, B. G. Knox and A. A. Theison (eds.) (Emmaus, Pa.: Rodale Press, 1981), pp. [illegible]1; E.D. Putt, "History and Present World Status," *Sunflower Science and Technology*, J. F. Carter (ed.) (Madison, Wis.: American Society of Agronomy, 1978), pp. 1-29.

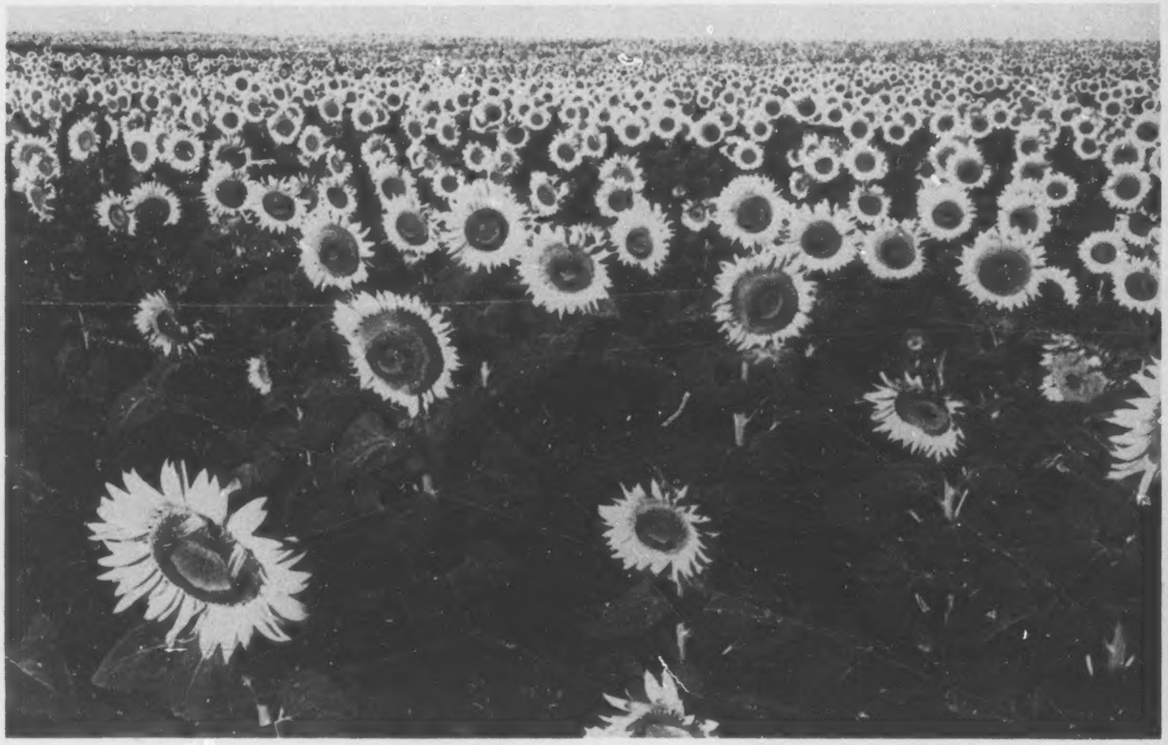


Photo credit: USDA-Soil Conservation Service

A field of sunflowers grown for oil, south of Forman, North Dakota

- current domesticated plants and animals are too demanding on the environment;
- conventional crops, forages, and livestock require unacceptably high energy inputs in the form of fuel, nutrients, pesticides, irrigation, or disease prevention; and
- the lack of diversified markets exposes farmers and ranchers to large foreign and domestic price instabilities.

Some of these concerns have been shown to be valid. For example, large geographic areas planted in hybrids with a common genetic background caused the rapid spread of corn blight in the 1970's, resulting in a nearly nationwide crop failure. Disease-resistant material in a germplasm bank was used to breed resistant plants for the next season, preventing the problem from continuing. A greater diversity of agricultural plants and animals serve as long-term investments and insurance for the future if they can alleviate such problems.

In the short term, different crops and forage plants and animals may be able to provide new profitable products and to diversify agricultural markets. Some plant products may provide unusual and high-value chemicals for the pharmaceutical, chemical, or energy industries, creating benefits for farmers and the Nation where such crops replace subsidized excess commodities or ones that exhaust important resources.

Some experts feel that "new" crops are needed especially for the arid and semiarid regions of the United States. Of the established crop plants, only barley, wheat, sorghum, certain beans, and cotton are adapted to dry conditions. Some of these have been bred for high production under heavy irrigation, decreasing their adaptation to drought. Other established crops, such as hybrid corn, were not originally arid-land plants and may have inherent limitations in genetic material.

Opportunities exist today for examining the potential of new plants and animals because of the uncertainty facing agriculture in the West. In some places irrigation is no longer possible. Lands need improvement to reach higher levels of productivity in other areas. Even in the large areas of the West that are too dry and prone to erosion for conventional tillage and harvest, it may be possible to increase agricultural productivity without jeopardizing important national resources. To this end, well-adapted plants and animals are being examined, often for production without irrigation, heavy fertilization or other large inputs.

ASSESSMENT

A study for the National Science Foundation identified 54 potential crops. Either these plants are adapted to environmental stress or provide a product critical to the needs of American society. Seven specifically are suited for arid or semiarid climates (table 61). Other authors have suggested additional potential crops for arid or semiarid zones. For example, Johnston (18) estimates that good evidence for medical usefulness exists for about 300 plant species of the Southwestern United States.

The status of these plants varies widely. Some, such as amaranth, tepary beans, guar, and cowpea, have a long history of use in the Americas. Therefore, they are new only to conventional agriculture. These plants are already domesticated, and their cultivation is well developed for certain types of agriculture. A sizable ethnic market exists for these products, and supply cannot meet demand. Now these old crops are ready for new and wider uses.

Other arid/semiarid-land plants are now being domesticated. Some are at early stages of development (jojoba, guayule, saltbush), whereas others are undergoing basic preliminary research (kochia, buffalo gourd, milkweed, *Euphorbia,* most medicinal plants).

The potential contribution to national productivity is not known for many of these crops. Preliminary assessments of biomass production indicate that levels are about one-fourth to one-half that expected from irrigated crops (19,22), but productivity would be expected to increase with plant breeding (table 62). High-production levels over wide areas may not be the goal for all crops, however. Some, such as the traditional varieties used by Papago desert farmers, may be best cultivated on smaller scales to maintain sources of already-adapted germplasm.

Table 61.—Information on Potential New Crops for Arid and Semiarid Lands

Crop	Life span	Part used	Product	Market competition	Adaptation	Land use competition	Cultural operations	Potential magnitude and significance	Needed work
Xerophytes:									
Buffalo gourd	Perennial	Seed	Protein and edible oil	Soybean	Dry	Desert	Mechanized	Large	Agronomic Machinery
Guayule	Perennial	Stem, root	Latex	Synthetic rubber	Dry	Cotton	Mechanized	Large	Agronomic
Jojoba	Perennial	Seed	Industrial oil	Sperm-whale oil	Dry, infertile	Desert	Hand labor	Large	Agronomic Machinery
Mung bean	Annual	Seed	Vegetable	Other beans	Dry	Sorghum	Mechanized	Medium	Agronomic
Pigeon pea	Perennial/annual	Seed	Bean	Cowpea	Dry, infertile	Peanuts	Mechanized	Small	Agronomic Demand
Pinyon pine	Perennial	Seed	Nut	Nuts	Dry	Forest	Hand labor	Medium	Agronomic Machinery
Tepary bean	Annual	Seed	Bean	Other beans	Dry, infertile	Range	Mechanized	Small	Agronomic Demand

SOURCE: Soil and Land Use Technology, Inc., A. A. Theisen, E. G. Knox, and F. L. Mann (eds.), *Feasibility of Introducing Food Crops Better Adapted to Environmental Stress"* (Washington, D.C.: U.S. Government Printing Office NSF/RA/780289, 1978), vol. I, p. 53, table 8.

Table 62.—Results of "New" Crop Experiments

Crop	Production (lb/acre)	Water available in growing region (in)
Amaranth (grain)	1,790	Not known (India)
Cowpeas (seeds)	895	5-10
Guar (seeds)	625-805	16-35
Mesquite	1,790	12-16
	12,530	24
Guayule	1,790-3,580	Irrigated
Kochia	9,845	16
Russian thistle	5,370-9,845	Not known
Saltbush	7,160	Not known (UT)
	5,370	Not known (TX)
Present crops	22,375	Irrigated

SOURCE: Various sources cited in: Wayne R. Jordan, Ronald J. Newton, and D. W. Rains, "Biological Water Use Efficiency in Dryland Agriculture," OTA commissioned paper, 1982.)

The development of "new" animals has received less attention than plants. Individual ranchers are experimenting with previously unused animals such as elk. Generally, these efforts are not well known and the people involved are isolated from one another and from the established animal science community.

These plants and animals face barriers of several kinds if they are to be used widely. Domestication, when necessary, is a time-consuming process, but sophisticated technology should shorten it significantly. Tissue culture techniques and other biotechnologies may contribute to the rapid development and dissemination of new germplasm and organisms. However, more formidable barriers—both technical and institutional—exist. A great deal of research remains to be done for many of the species described here, and there is little evidence to suggest that major Federal or State initiatives will be forthcoming. Often, extensive field testing has not been completed.

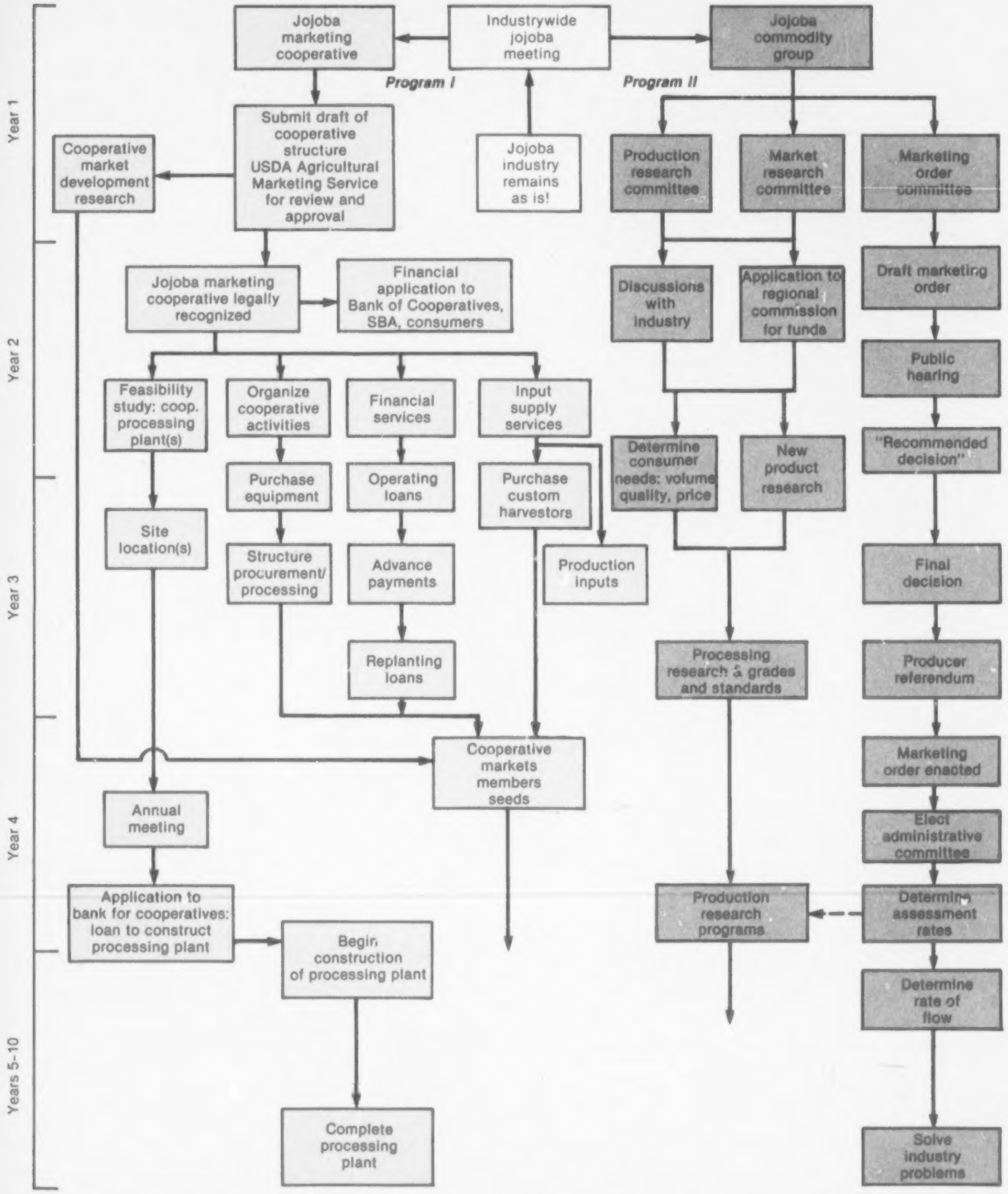
Once these crops produce acceptable yields under field conditions, they must be attractive to producers and must find markets. There have been previous attempts, both successful and unsuccessful, to introduce new crops. Experience shows that markets and the institutional infrastructure for adoption are crucial to success. For example, processing plants may be required, commodity organizations may be necessary, consumers may have to be educated about new products, and marketing channels from farm to consumer may have to be developed (fig. 60). Even then, the adoption of a new crop is unlikely to be entirely predictable.

Once a market for a new product exists, germplasm will probably be available to all interested growers. At the early stages of introduction, however, new crop production may be limited to large landowners with the capital and interest for major new ventures. For plants with industrial uses, this may require corporations to develop processing facilities first, then to obtain raw plant materials from local farmers on a contract basis or to grow them on their own land.

Generally, there are few legal barriers to the introduction of new crops or animals. A major exception, however, relates to reclamation of arid and semiarid surface-mined lands. Both Federal and State laws restrict the kinds of nonnative plant species that may be used for mineland revegetation. Therefore, potential new crop or forage plants that are not U.S. natives often cannot be included in some of the largest research programs and experimental plantings. Similarly, State laws that regulate ownership of wildlife and Federal regulations that control slaughtering and quarantine of imported organisms are cases where the adoption of technology is restricted legally. While these legal restrictions are small compared to the social and economic barriers faced by new products, they can be significant.

Generally, these drought-adapted agricultural products have the potential for tailoring agriculture more closely to prevailing environmental conditions. Where resources—e.g., soils or water—are being used faster than they are replenished, adapted organisms hold hope for a more sustainable type of agriculture. For example, desert milkweeds may be able to replace dryland crops in the western Great Plains where increasing energy costs are eliminating irrigation (1). Or, where fragile lands have been plowed for annual crops and severe erosion has resulted, adapted perennial shrubs, grasses, and forbs may provide profitable products without land degradation. Such potentials are usually long term. Few of the crops discussed

Figure 60.—The Complex Production, Marketing, and Consumption Scheme For a New Crop Entering the Commercial Market. This Diagram Illustrates a Potential Strategy for Jojoba Producers and Processors


Year 1
Year 2
Year 3
Year 4
Years 5-10
Jojoba marketing cooperative
Industrywide jojoba meeting
Jojoba commodity group
Program I
Program II
Submit draft of cooperative structure USDA Agricultural Marketing Service for review and approval
Cooperative market development research
Jojoba industry remains as is!
Production research committee
Market research committee
Marketing order committee
Jojoba marketing cooperative legally recognized
Financial application to Bank of Cooperatives, SBA, consumers
Discussions with industry
Application to regional commission for funds
Draft marketing order
Public hearing
Feasibility study: coop. processing plant(s)
Organize cooperative activities
Financial services
Input supply services
Purchase equipment
Operating loans
Purchase custom harvestors
Determine consumer needs: volume quality, price
New product research
"Recommended decision"
Site location(s)
Structure procurement/ processing
Advance payments
Production inputs
Final decision
Replanting loans
Processing research & grades and standards
Producer referendum
Cooperative markets members seeds
Marketing order enacted
Annual meeting
Elect administrative committee
Application to bank for cooperatives: loan to construct processing plant
Begin construction of processing plant
Production research programs
Determine assessment rates
Determine rate of flow
Complete processing plant
Solve industry problems

SOURCE: G. L. Laidig, "Jojoba, *Simmondsia chinensis*," *Feasibility of Introducing New Crops: Production-Marketing-Consumption (PMC) Systems*, E. G. Know and A. A. Theison (eds.) (Columbia, Md.: Soil and Land Use Technology, Inc., 1981), pp. 74-101.

Box V.—Rules, Regulations, and "New" Agricultural Plants

Federal and State laws restrict the types of plants that may be used for reclamation of surface-mined lands. These legal limitations have had unexpected results on rangeland research programs.

The primary intent of most laws was to ensure a self-sustaining and persistent plant ground cover to protect soils. For example, Wyoming law requires that mine operators:

> . . . establish . . . permanent vegetative cover of the same diverse seasonal variety native to the area or of a species that will support the approved post-mining land use. This cover shall be capable of stabilizing the soil.

Wyoming law did not seek to prevent the use of all nonnative plant species but only those that: 1) were not self-renewing and required special management for persistence, or 2) gave a false impression of reclamation success and might encourage damaging early grazing. The unintended result of the law, however, was the limitation of introduced plants in many reclamation and rangeland programs.

Is this desirable? The question is still being debated. Some contend that the focus on using and improving native forage plants is long overdue and that it might lead to new styles of agriculture more adapted to arid/semiarid regions. Others believe that plant specialists should have worldwide germplasm at their disposal and that introduced plants may provide important new additions to American agriculture. For the time being, constraints on the use of nonnative plants provide an uncommon example of legal limitations on plant research.

SOURCE: Wyoming Department of Environmental Quality, *Land Quality Division Rules and Regulations*, ch. IV.3.D.(2), August 1982.

here, with the possible exception of grain amaranth, are on the verge of becoming major national commodities, but timely research and development are likely to provide important payoffs with sustained support. The domesticated desert crops such as cowpea and tepary bean, since they are adapted for cultivation now and have developed markets, deserve especially close examination.

Plants for Food and Forage

Grain amaranth was a staple crop of Central American Indians before colonizers, in order to eradicate native cultures, methodically destroyed the fields. The remaining amaranth germplasm is highly variable, providing rich materials with which to work. Amaranth could provide biomass energy, seed starch, or leafy vegetables, but its high-protein grain is most promising. Both leaves and seeds contain proteins rich in lysine and methionine, amino acids that limit protein digestion in other grains (table 63). Amaranth is well suited to semiarid conditions but not to prolonged or excessive drought; some plants are adapted to nutrient-deficient soils but others require substantial fertilization. An accelerated program of amaranth research and development is underway at the Organic Gardening and Farming Research Center in Emmaus, Pa. The National Academy of Sciences and the National Science Foundation sponsor amaranth research and USDA is also showing interest (30).

Table 63.—The Protein Content and Quality of Various Grains

Grain	Protein (%)	Limiting amino acid(s)	Relative protein score (100 points optimum)
Amaranth . . .	15	Leucine	67
Barley	9	Lysine	58
Buckwheat . .	12	Leucine	83
Corn	9	Lysine	35
Oats	15	Lysine	62
Rice	7	Lysine	69
Soybeans . . .	34	Methionine, cysteine	89
Wheat	14	Lysine	47

SOURCE: J. P. Senft, "Protein Quality of Amaranth Grain," *Proceedings of the Second Amaranth Conference* (Emmaus, Pa.: Rodale Press, Inc., 1980), p. 45.

Cowpeas, grown for their dry seeds in semiarid regions of the world, sometimes produce seeds in years when drought causes other crops

Photo credit: Rodale Press, Inc.

This grain amaranth plant was selected for its compact form

to fail. Cowpea vegetation makes excellent hay, and cowpea's high-protein seeds can be used as animal protein concentrates. Green cowpeas are used now in the U.S. commercial canning industry.

Buffalo gourds are native undomesticated plants with wide distribution in the Western United States. Each plant produces an abundant crop of gourds with oil and protein-rich seeds and plant roots contain high-quality starch (table 64). Its vines are a potential forage that can be repeatedly harvested. It is also reported to contain medicinal compounds. Domestication programs began for buffalo gourd in 1973 at the University of Arizona.

Plants for Biomass Energy

Current energy prices do not encourage the development of biomass crops. Some experts believe that fragile arid and semiarid lands should not be used for biomass production under most circumstances. But conditions may change, and with appropriate safeguards, the following plants may have potential for producing biomass and other products.

Table 64.—Starch and Moisture Content of Several Sources of Starch

Name of starch	Source	Moisture (%)	Starch (%)
Buffalo gourd[a] root	*Cucurbita foetidissima*	68-72	15-17
Potato	*Solanum tuberosum*	75-78	19
Tapioca	*Manihot utilissima*	60-75	12-33
Arrowroot	*Maranta arundinaceae*	65-75	22-28[b]

[a] Only buffalo gourd is an arid-land plant.
[b] Industrial starch yield is typically 15 percent owing to cell structure.

SOURCE: W. P. Bemis, J. W. Berry, and Charles W. Weber, "The Buffalo Gourd: A Potential Arid Land Crop," *New Agricultural Crops*, G. A. Ritchie (ed.) (Boulder, Colo.: Westview Press, 1979), p. 85.

Mesquites are a diverse group of woody legumes from North and South America. While they are commonly considered pests by ranchers, they have a long history of use for wood, flour, and fuel by other cultures. Mesquite grows in areas of low rainfall by tapping ground water, thus creating a potential problem in some areas. Annual yields are currently low and plants are usually sensitive to low temperatures. But mesquite is one of the few nitrogen-fixing legumes that can tolerate salinities equivalent to seawater and its diversity provides material from which to breed improved varieties.

Saltbush is a common Western drought-resistant shrub. Many species have protein concentrations equivalent to that of alfalfa so it is important for forage. It has also been important in revegetating disturbed lands.

Kochia (tumbleweed) and Russian thistle are both "weeds" with potential for biomass fuel as well as forage. Their reputation as weeds may hamper acceptability but it can also be exploited for high productivity.

In other cases, agricultural residues can be used for biomass energy, plant and animal residue have potential (15).

Plants for Industrial Products

Guar is a leafy annual legume that produces gum and forage. Guar gum is a strengthening and stabilizing agent in paper, cosmetics, processed foods, and industrial materials. Older plants withstand drought, and plant seeds withstand alkaline or saline conditions. In 1977, 20,000 tons of guar were produced but demand exceeded supply. U.S. consumption is expected to be 41,500 tons in 1983 (31).

Guayule is a wild shrub, native to Mexico and Texas. It is adapted to regions with low and erratic rainfall. Plant roots and shoots contain rubber comparable to that produced by the Asian *Hevea* rubber trees, rubber that cannot be duplicated synthetically. Guayule appears to be suitable for mechanized agriculture and requires little fertilization. It is not very salt tolerant. and guayule plantations are currently susceptible to insects and diseases. The Native Latex Commercialization Act of 1978 (Public Law 95-592) was designed to stimulate guayule production, and the commercial rubber industry is involved in guayule research and development. Two other sources of arid/semiarid lands natural rubber are rabbitbrush and sunflowers.

Soaps for shampoos are extracted from various species of yucca, and wax obtained from the seeds of jojoba is used for a variety of cosmetics. Neither plant has been cultivated in the United States but relatives of the yucca are grown in other parts of the world. Jojoba grows in Arizona, California, and Mexico on infertile or saline soils where rainfall is scarce. Jojoba wax is a substitute for sperm whale oil, with a large number of potential commercial uses in the cosmetic, pharmaceutical, and machinery industries. The first large-scale irrigated commercial jojoba plantations are expected to come into production in the Southwest in 1983. At that time the price for seeds should decrease, and the high-volume, low-cost lubricant market should open.

Many species of plants produce copious amounts of hydrocarbons that can provide chemicals or be cracked to liquid fuels. The principal species under development are milkweeds, gopherweed, and rabbitbrushes. Milkweeds could provide a variety of chemical products such as inositol and pectin and perhaps stimulate development of a honey bee industry. Gopherweed produces a milky latex that can be harvested without destroying the plant. Candelilla produces a wax with a high melting point, and is a product imported from Mexico. Candelilla wax sells for $4.19 per kilogram ($1.90/lb) and the market is good (9).

Animals for Arid and Semiarid Lands

The American bison, or buffalo, was once the most important large grazer of Western lands. Bison have recovered from near extinction, and several large public and private herds now exist (table 65). Buffalo ranchers suggest that these animals are more adapted to grazing on semiarid lands than are their domestic counterparts. They claim that buffalo use low-productivity resources frugally, produce high-quality meat, and generally exhibit greater hardiness than do domestic livestock.

Rabbits also have potential as new agricultural animals. They have short gestation periods, multiple births, and short parenting time. None of these features is shared with major domesticated animals of rangelands, and such characteristics provide the fastest way to increase animal productivity per unit of plant productivity (table 66). Rabbit farming is now practiced on a small scale, but the potential for open-range ranching is unknown. Control, containment, and slaughtering methods have not

Table 65.—Buffalo Sales in 1981

Sale	Number of animals[a]	Average price
Dakota Heritage Buffalo Sale, Mitchell, S. Dak.	131	$572
Wichita Mountains Wildlife Refuge, Cache, Okla.	123	$487
Kansas Fish and Game Commission, Canton, Kans.	56	$582
Custer State Park Hermosa, S. Dak.	470	$444
Durham Ranch	700	b

[a] These figures include only one of the many private herds.

[b] Average price not available; individual price range $450 to $1,000.

SOURCE: National Buffalo Association, "1981 Sales Results," *Buffalo* 10(1), 1982, pp. 8-9.

Table 66.—A Comparison of Cattle, Sheep and Rabbit Production on Western Rangelands

Feature	Rabbits	Sheep	Cattle
Offspring/100 females	1,485	120	90
Weight per offspring (kg)	1	39	182
Population replaced annually (%)	30	20	10
Offspring harvested annually/100 females	1,455	100	80
Harvested weight/female (kg)	13	39	145
Energy use per individual (kcal)	200,000	1,600,000	9,000,000
Energy use per kg of offspring (kcal)	19,000	40,000	62,000

SOURCE: Adapted from C. W. Cook, "Use of Rangeland for Future Meat Production," *Journal of Animal Science* 45:1480, 1977, table 4.

been developed, and large populations of uncontrolled rabbits have sometimes become major pests. Limited markets are a major constraint to developing a Western rabbit industry.

Limited experiments are underway on replacing single-species domestic livestock with mixtures of species. The highest potential for these approaches appears to be on rangelands where multiple use is important (ch. XI).

Salt-Tolerant Organisms

INTRODUCTION

Salts occur in agricultural soils for a number of reasons. Some soils and ground water supplies are naturally saline, and both soils and water can gain salt from agricultural practices such as fertilization and irrigation. These processes are heightened in arid and semiarid lands. High rates of evaporation and transpiration return pure water to the atmosphere, leaving salts behind. The chemical characteristics of the salts vary. Chloride salts of sodium (table salt), calcium, and magnesium are all common, but sulfates and carbonates sometimes may replace the chloride ions. Large areas of nonirrigated croplands and rangelands in the northern Great Plains are experiencing salinity problems, but irrigated areas, especially in California and Arizona, are most affected.

Usually plant growth suffers once soils or water are salinized. Salty water is difficult for plants to extract from soils, and such soils often contain high levels of potentially toxic ions (24). Most common agricultural plants cannot tolerate salinities of 10 to 20 percent seawater. Many are sensitive to even lower concentrations (table 67).

The productive life of salinized areas could be extended by careful and intensive management. Current management technology, such as drain installation or periodic flushing with large amounts of water, has emphasized an engineering approach. Often this is costly in terms of dollars, energy, and water. Economically feasible engineering approaches do not eliminate salt; they only minimize it. Therefore, some experts believe that the development of salt-tolerant crops would provide an important biological method to supplement current management technologies. These plants might be suitable for land currently too saline for agriculture, or they might be irrigated with lower quality irrigation water, thus "saving" higher quality water for use on those plants that require it.

The use of salt-tolerant organisms is not limited to flowering plants. A number of programs are underway that use algae and micro-organisms to produce biomass for food or energy in brackish or saltwater culture. Both indoor and outdoor systems are used. Such systems could be used in conjunction with carbon dioxide emissions from coal generators or salt-gradient ponds to increase productivity or to generate solar energy (26) and would be another way to produce agricultural products while using water too salty for most current crops.

Proponents of these technologies do not advocate increasing the salinity of soil or water nor the indiscriminate use of saltwater irrigation. Instead they stress the need for continuous evaluation and careful management

ASSESSMENT

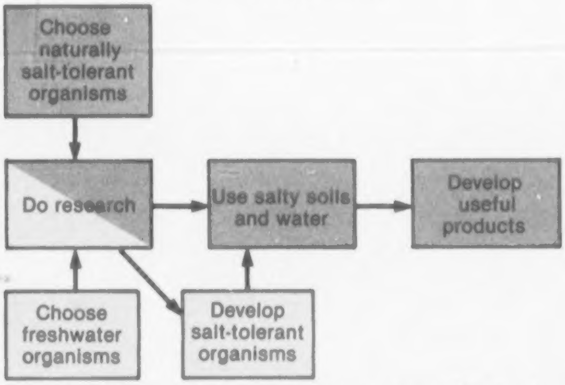
There are two approaches to developing salt-tolerant flowering plants: adding genetic salt tolerance to conventional crop and forage plants or developing naturally salt-tolerant, or halophytic, plants into productive agricultural species (fig. 61).

Table 67.—Salt Tolerance of Crops

	Salt tolerance		
Type of crop	Low	Medium	High
Fruit	Avocado Lemon Strawberry Peach, apricot Almond, plum Prune, grapefruit Orange, apple, pear	Cantaloupe Date Olive Fig Pomegranate	Date palm
Vegetables	Green bean Celery Radish	Cucumber, squash peas, onion Carrot, potato Sweet corn Lettuce Cauliflower Bell pepper Cabbage Broccoli Tomato	Spinach Aspragus Kale Garden beet
Forages	Burnet Red clover Meadow foxtail White Dutch Clover	Milkvetch Sour clover Meadow fescue Oats (hay) Wheat (hay) Rye (hay) Tall fescue Alfalfa, Sudan grass Mountain brome White sweet clover	Barley Western wheat grass Canada wild rye Bermuda grass Nuttall alkali grass Salt grass
Field Crops	Field bean	Castor bean Sunflower Flax, corn Sorghum (grain) Rice, oats (grain Wheat (grain) Rye (grain)	Cotton, rape Sugar beet Barley (grain

SOURCE: D. Todd, *Ground Water Hydrology* 2d ed. (New York: John Wiley & Sons, Inc., 1980).

Figure 61.—Two Methods for Producing Salt-Tolerant Organisms


Choose naturally salt-tolerant organisms
Do research
Use salty soils and water
Develop useful products
Choose freshwater organisms
Develop salt-tolerant organisms

SOURCE: J. C. Aller and O. R. Zaborsky, "The Biosaline Concept," *The Biosaline Concept*, A. Hollaender (ed.) (New York: Plenum Press, 1979), p. 6.

Halophytes

Some experts feel that the halophyte approach may be more powerful since halophytes are adapted already to salty water and soil and are, in some cases, exceptionally productive (2). For example, some of these plants are more productive than alfalfa and grow in water at least as salty as seawater.

Salt tolerance is scattered widely among wild flowering plants. Various halophytes are potential forage crops, ornamentals, potherbs, vegetables, grains or berries (table 68). All halophytes are not arid- or semiarid-land plants. However, a world-wide search for promising desert germplasm resulted in about 1,000 accessions from Argentina, Australia, Brazil,

Table 68.—Halophytes With Potential for Agricultural Use

Common name[a]	Potential use	Comments
Palmer's saltgrass	Grain	Used by Cocopa Indians, Gulf of California
Batis	Edible root	
Cord grass	Forage, grain	Feeds cattle, Argentina
Glasswort		23 MTU/ha; seawater irrig.[b]
Saltbush	Forage, grain	Seed yield 1 T/ha; 16% protein
Cressa.....................	Animal feed	
Maireana	Forage	Feeds cattle, Australia
Mesquite	Forage	Feeds livestock, 20,000 ha, Chile

[a] Scientific names are given in the appendix.
[b] MTU/ha = metric tons per hectare.

SOURCE: N. P. Yensen, M. F. Fontes, E. P. Glenn, and R. S. Felger, "New Salt Tolerant Crops for the Sonorhan Desert," *Desert Plants* 3(3):111-118; G. F. Somers, "Natural Halophytes as a Potential Resource for New Salt-Tolerant Crops: Some Progress and Prospects," *The Biosaline Concept*, A. Hollaender (ed.) (New York: Plenum Press, 1979), pp. 101-105.

Chile, New Zealand, Peru, and South Africa. Twenty-four species were identified from the Sonoran Desert (32).

Some of these arid-land plants are known to be useful and edible: they were gathered and eaten by native people in the past. Most, however, have neither been used nor cultivated. Extensive research is required before they can make an impact on agriculture, a process that may take at least 50 years.

Conventional Crops

A wide variety of conventional crops is currently being evaluated for variations in salt tolerance. Those plants that possess unusually high salt tolerances are being evaluated further. As of 1980, North American research on such crops occurred at seven U.S. localities and at least three Canadian sites. The plants evaluated include alfalfa, cowpeas, mung beans, melons, cucurbits, tomatoes, wheat, lettuce, dates, and grapes. Israeli scientists are also involved: they are working with tomatoes, cotton, wheat, and sugar beets, as well as fodder and landscaping plants.

Screening for salt tolerance among only commonly grown varieties of crop plants appears unpromising. Much of the variability of these crops in salt tolerance may have been lost during breeding for other traits. Therefore, breeders have turned to the large seed collections held in germplasm banks around the world. For example, several thousand barley and wheat accessions from USDA collections were screened and irrigated with various dilutions of seawater in California (13). In some cases, single species collections are not promising. Germplasm from wild relatives may be required to supplement the low salt tolerance in these plants. Because this was true of tomatoes, crosses were begun with a wild, commercially useless tomato from the Galapagos Islands.

Other scientists are using tissue culture techniques to achieve results, a method that saves both time and space. For example, millions of cells, each a potential plant, can be grown in a 4-inch dish. If the dish contains salty growth media, only the tolerant cells will survive. This technique has been used for cell lines of wheat, oats, and tobacco. Results indicate that enhanced salt tolerance sometimes persists and can be passed on to offspring. Experiments are also underway on sugar beets, tomatoes, and corn. This approach cannot be applied to all plants now. Some species cannot be cultured and regenerated yet and other species lose their capacity for regeneration too quickly (8).

These experiments are preliminary, and it will be some time before salt-tolerant strains are ready for commercial use. There is another disadvantage: it appears now that salt tolerance is gained at the expense of productivity.

Micro-Organisms

The cultivation of marine and brackish water algae is short compared to cultivation of agricultural crops on land. Most of the technology is Asian; major research efforts in Western countries are recent. Many of the larger species have been cultivated in offshore beds using biological breakthroughs to supplement older technology. Smaller organisms, such as microscopic algae, blue-green algae, and bacteria, are harvested from inland ponds. The latter technologies may be adaptable to arid and semiarid lands. For example, Mexico produces large amounts of the high protein, blue-green alga, *Spirulina,* in large ponds and processing facilities and Israeli scientists are experimenting with the same organism in brackish water ponds in the Negev Desert.

Some of these organisms can be very productive in saltwater. Microalgae used in Hawaiian experiments produced 60 tons of biomass per acre per year in small outdoor ponds. Smith (26) speculates that such ponds would be a way to use brine left from the process to improve salty irrigation waters.

General concerns remain about the desirability of developing salt-tolerant crops, regardless of the method used. It may be futile to develop salt-tolerant forages if the plant material is too salty for animals. Saltwater irrigation presents other potential problems. Without intensive management, ground water contamination may result, decreasing the quality of freshwater. The situations in which salt-tolerant crops provide an unusual opportunity are limited. Such crops are not a panacea for the mismanagement of irrigated lands.

CONCLUSIONS

A large number of opportunities to improve agriculture in arid and semiarid lands exists. Some technologies will not increase production in the usual sense. For example, the ability of plants and animals to survive harsh conditions may sometimes be as important as high yield. Attempts to decrease total plant water use have often failed in the past. New approaches, such as plant breeding for environmental stress, are more promising. The biotechnologies are blossoming with unpredictable results. While it is clear that agriculture is changing, it is not clear how older institutions will adapt to these changes.

The technologies that affect water-use efficiency are powerful, and the choice of goals to which they are applied is crucial. Efforts to improve drought resistance of existing agricultural plants and animals is quickening. Perhaps faster and larger gains can be made by applying these technologies to "new" arid/semiarid land plants. Rich germplasm from underused desert crops and wild plants is available to decrease water use while maintaining agricultural production. Although this is an important long-term goal, it cannot be achieved immediately.

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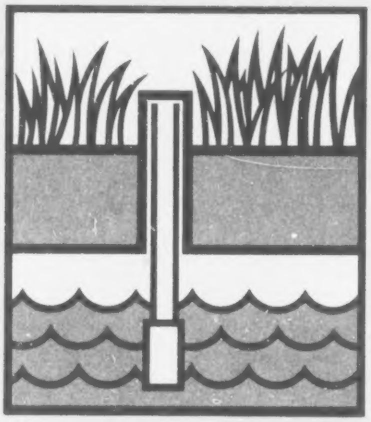
Appendix 9-1.—Scientific Names of Potential "New" Agricultural Plants

Crop	Scientific name
Group I:	
Buffalo gourd	*Cucurbita foetidissima* HBK
Cowpea	*Vigna unguiculate* (L.) Walp.
Euphorbia	*Euphorbia* spp.
Grain amaranth	*Amaranthus* spp.
Guar	*Cyamopis tetragonoloba* (L.) Taub
Guayule	*Parthenium argentatum*
Jojoba	*Simmondsia chinensis* (Link) Schneider
Kochia	*Kochia scoparia* (L.) Roth
Mesquite	*Prosopis* spp.
Saltbush	*Atriple* spp.
Group II. Halophytes:	
Batis	*Batis maritima* L.
Cord Grass	*Spartina longispica*
Cressa	Cressa truxillensis
Glasswort	*Salicornia europaea* L.
Maireana	*Maireana brevifolia*
Mesquite	*Prosopis algorobo*
Palmer's saltgrass	*Distichlis palmeri* (Vasey) Fassett
Saltbush	*Atriplex patula*, var. *hastata*



Technologies Affecting Ground Water

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Chapter X

Technologies Affecting Ground Water

Ground water resources have become increasingly important to Western agriculture in the past decades, since increased use of ground water allows large new areas of land to be irrigated. Concerns exist that such use is not sustainable over the long term and that more careful decisions must be made to protect the valuable, finite water resource.

This chapter assesses ground water's role in agriculture and in other uses in the Western United States and evaluates technologies associated with its use. The chapter discusses ground water availability, water-quality degradation, and the interrelated character of ground and surface water, with emphasis on broad ground water principles applied to technologies and problems of the arid and semiarid West. Technologies designed to manipulate ground water quantity and quality are discussed separately to reflect the fact that, in general, water-supply technologies may involve active management, while water-quality technologies generally require a more passive approach. In practice, this separation seldom exists.

A wealth of information exists on ground water supplies and quality in the individual aquifers of the Western United States, but a regional synthesis was not found in the literature and may not exist. The recent trend toward sophisticated computer models has produced a competence for detail, but has exacerbated the problem of gaining an overview of this resource.

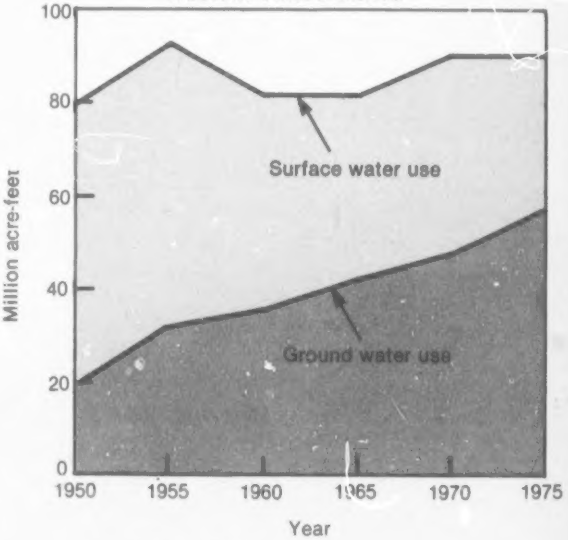
THE WATER SETTING

Ground Water Use in the Western United States

During the past three decades, ground water use in the Western United States has almost tripled, and the percentage of total withdrawals coming from ground water has nearly doubled, from 21 percent in 1950 to 39 percent in 1975 (fig. 62). Ninety-six percent of the ground water used in the entire United States occurs in the 17 Western States. Agriculture, including rural domestic water use, relies heavily on ground water (fig. 63), but the absolute and relative amounts involved vary greatly within the region (table 69).

Major Western aquifer areas in heavy use are the Ogallala (or "High Plains") aquifer, which stretches south from Nebraska to the Texas panhandle, the aquifers of the interior valleys of California, and those of the Snake River plain in Idaho. Each of these ground water areas supplies a significant percentage of the total irrigation and domestic water used in these areas. In other areas, however, the importance of an individual aquifer is more local.

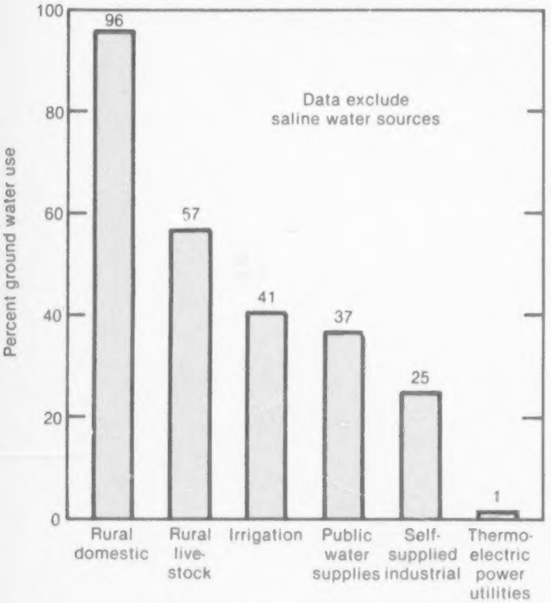
Figure 62.—Ground and Surface Water Use in the Western United States



Ground water withdrawals rose from 21 to 39 percent of total water withdrawals during the period from 1950 to 1975. These data include the nine water resource regions of the West; such trends cannot be sustained.

SOURCE: Office of Technology Assessment, 1982. (Original source: U.S. Geological Survey, *Estimated Use of Water in the United States*, published at 5-year intervals.)

Figure 63.—Ground Water's Contribution to Various Water Uses, 1975



In 1975 approximately 96 percent of the water for rural domestic use came from ground water. Rural livestock also derived a large share of their water from ground water supplies.

SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980). (Original source: C. Richard Murray and E. Bodette Reeves, *Estimated Use of Water in the U.S. in 1975*, U.S. Geological Survey Circular 765, 1977.)

The extent of ground water withdrawals in excess of recharge, or "mining," is also a local problem. With the exception of a few areas (e.g., Texas and Arizona) where obvious declines in the regional water table are being noted, the relationship between recharge and pumping is quite speculative.

The perception that ground water is an inexhaustible resource has gradually changed during the last 30 years. Ground water is increasingly viewed as a finite resource that is being overdrafted. Both the National Water Commission (7) and the U.S. Water Resources Council (WRC) (15) discussed the sustainability of activities based on ground water extraction and concluded that much of the irrigated agriculture in areas such as Texas, Oklahoma, and Kansas which are heavily dependent on ground water (primarily the Ogallala aquifer), probably are not sustainable. Further study of this region by the High Plains Associates (5) outlined some of the effects of diminishing water and energy resources at the local, State, regional, and national level.

Ground water overuse and its effects on agriculture (i.e., abandonment of once productive farmland, higher pumping costs, and land subsidence) are only one element of the perceived problem, however. The deterioration of ground water quality, resulting from the infiltration of agricultural, industrial, and municipal pollutants may be of even greater significance for future ground water use in the Western United States. Most rural uses involve untreated water, and the quality of this water is therefore of great importance, especially to those users requiring high quality, such as domestic rural users (ch. IV).

Table 69.—The Importance of Ground Water in Different Western Regions, 1975

Region	Total withdrawal all sources	Total withdrawal ground water	Percent ground water of total withdrawal	Overdraft	
				Total (maf)	Percent (maf)
Missouri	42.6	11.7	27	2.9	24.6
Arkansas-White-Red	14.4	9.9	69	6.1	61.7
Texas-Gulf	19.0	8.1	43	6.3	77.2
Rio Grande	7.1	2.6	37	0.7	28.1
Upper Colorado	7.7	0.1	1.0	0	0
Lower Colorado	10.0	5.6	56	2.7	48.2
Great Basin	9.0	1.6	18	0.7	41.5
Pacific Northwest	42.0	8.2	20	0.7	8.5
California	44.4	21.5	48	2.5	11.5

Note: All volumetric data in million acre-feet (maf), conversion from million gallons per day (mgd) and rounded to nearest 0.1 maf.

SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, *Summary*, vol. 1, 1978), pp. 18-25.

Box W.—When the Well Runs Dry—The High Plains Study

In 1976, prompted by concern about the diminishing ground water supplies in the Ogallala aquifer and possible effects on irrigated agriculture in the six High Plains States (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas) underlain by the aquifer, Congress authorized and funded the High Plains study (Water Resources Development Act of 1976, Public Law 94- 587). Congress gave major responsibility to the U.S. Department of Commerce; the U.S. Army Corps of Engineers was assigned the task of planning and evaluating the potential for interbasin transfer of water to the High Plains.

Five major policy alternatives for the High Plains study were evaluated: 1) no change in public water policy; 2) increased education and research to improve water use efficiency; 3) new regulations restricting the amount of water pumped for irrigation; 4) intrastate surface water development; and 5) interstate surface water development. The effect of each policy was considered for total irrigated acres, crop-production volumes, total returns to land and management, number of acres shifting to dryland production, changes in ground water levels, water use, sales volumes by economic sector, employment, and population. Values were estimated for the years 1977, 1985, 1990, 2000, and 2020.

According to the scenarios developed by the study, projections of future crop production do not indicate a significant change in the current mix of crops and relative size of their production volume to 2020. Instead, the problem of ground water depletion and disruption in irrigated crop production is localized within States. Education and research on water conservation and legal restrictions on pumping could slow depletion of the aquifer. Intrastate and interstate surface water development also could help slow ground water depletion but would require large economic investments and entail extensive environmental and social costs.

SOURCES: High Plains Associates, "Six-State High Plains Ogallala Aquifer Regional Resources Study, Summary," A Report to the U.S. Department of Commerce and the High Plains Study Council, July 1982. Raymond J. Supalla, Robert R. Lansford, and Noel R. Gollehon, "Is the Ogallala Going Dry?," *J. Soil and Water Cons.* 37:310-314.

Ground Water Characteristics

Ground water may result from a number of processes:

1. infiltration of precipitation;
2. seepage through the banks and beds of surface water bodies such as ditches, rivers, lakes, and oceans;
3. ground water leakage and inflow from adjacent aquifers; and
4. artificial recharge from irrigation, reservoirs, water spreading, and injection wells.

There is "misinformation, misunderstanding, and mysticism" (7) about ground water that credits it with occurrence in underground rivers, pools, and veins, and thus separating "percolating" underground water from "underground streams." Ground water does not occur in pools or channels of the kinds commonly seen on the surface, with a few exceptions, such as in some limestone or basalt formations. Instead, it is found usually in small open spaces, or interstices, of subsurface geological formations of rock or unconsolidated sediment.

Ground water represents a vast and largely unmeasured natural storage reservoir. Although nearly all rocks contain some water, rocks that yield significant quantities of water are known as "aquifers." The subsurface layers of the earth, below the soil moisture zone, comprise a great reservoir through which water moves very slowly. Its journey underground may be extremely brief or very long. This reservoir acts as a vast natural regulator in the hydrologic cycle, comparable in its effects to the oceans. It absorbs some fraction of the rainfall and snowmelt that would otherwise reach streams and rivers very rapidly as surface runoff, and it maintains streamflow during dry periods when no surface runoff occurs.

Only a small proportion of the total subsurface zone saturated with ground water is composed of rocks that store and transmit significant amounts of water. A wide range of permeabilities exists, ranging from cavernous limestones that may transmit water in much the same fashion as surface rivers and streams, to semipermeable layers that transmit water imperceptibly and that are not important in moving water to a spring or well.

In all cases, the deeper levels of the ground water zone consist of interstices that are so few and small that further downward percolation of water is impossible. Generally, the amounts of water to be found below a depth of 2,000 to 3,000 ft below the surface are very small, except in exceptional circumstances.

If inflow to a ground water system exactly equals outflow from that system, storage remains constant and the ground water will be a renewable resource. Ground water that is used at a rate in excess of recharge, no matter what the total available volume may be, is being "mined," and its use is not renewable. Agricultural development based on such mining will ultimately be threatened. For example, irrigated agriculture in the High Plains region of Texas was based on ground water development. The ground water used for irrigation has been mined from the Ogallala aquifer in excess annual recharge to that aquifer. In a period of slightly more than 20 years, some irrigated acreage is reverting to nonagricultural uses or other types of agriculture (e.g., limited irrigation, rangeland agriculture, and dryland farming) as the ground water reserves of the Ogallala aquifer in that area have been depleted or energy costs of pumping have become prohibitive.

In arid and semiarid areas, ground water inflow from adjacent aquifers, particularly those found in higher level ground water basins, may be important in local ground water recharge. The actual effect of this at a particular site is difficult to determine without detailed studies of the meteorological and geological site characteristics. Attempts to recharge overdrafted aquifers artificially have increased in recent years, particularly in areas of water shortage and may be locally significant.*

Western Ground Water Regions

Ground-water resource regions are more difficult to define than are surface-water resource regions. While surface-water resource regions may be differentiated on the basis of topographic divides, ground-water resource regions must be separated on the basis of varying rock types and surface climate. Arbitrary decisions concerning the relative importance of these factors must be made in assigning an area to a given ground-water resource region. Thus, various experts may have slightly different opinions concerning the placement or definition of the controlling factors for a particular site. A given ground water region may be comprised of a number of surface water basins.

For purposes of this assessment the major ground-water resource regions of the Western United States are defined as:

1. Western Mountain Ranges,
2. Alluvial Basins,
3. Columbia Lava Plateau,
4. Colorado Plateaus and Wyoming Basin,
5. High Plains,
6. Unglaciated Central Region, and
7. Glaciated Central Region (fig. 64).

These regions are discussed in detail in appendix B.

Relationships Between Ground and Surface Waters

The distinction between ground water and surface water is largely arbitrary. Water moves between these two environments continuously. It is not accidental that those areas of the Western United States now experiencing, or beginning to experience, ground water supply or quality problems are commonly areas of sur-

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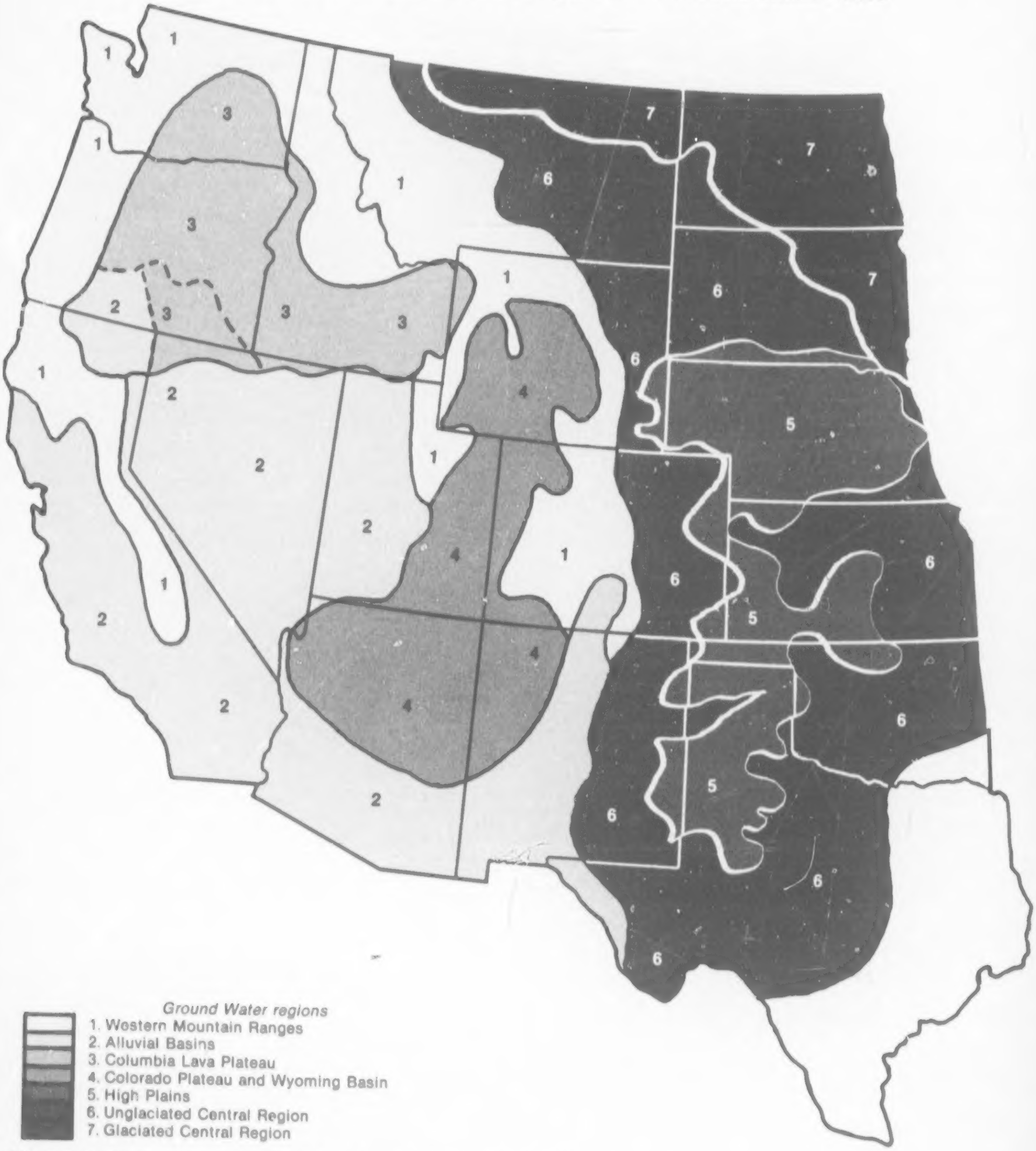
*In May 1983, the U.S. House of Representatives passed a measure (H.R. 71) that would study and establish demonstration projects for ground water recharge in the High Plains. Other Western States facing ground water depletion were to be included in the study as well.

Figure 64.—The Major Ground Water Regions of the Western United States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Ground Water regions
1. Western Mountain Ranges
2. Alluvial Basins
3. Columbia Lava Plateau
4. Colorado Plateau and Wyoming Basin
5. High Plains
6. Unglaciated Central Region
7. Glaciated Central Region

SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980).

face water shortage. Only in certain special geological settings is it possible to decrease the amount of water contained in one part of the hydrologic cycle without also decreasing the amount in others.

Where ground water occurs in direct contact with surface water bodies such as lakes, ponds, or rivers, there will commonly be a movement of water between the two. The direction of this movement normally will be determined by the difference in altitude between the two sources. In arid and semiarid lands, where evapotranspiration losses normally far exceed precipitation amounts, the few perennial or intermittent streams are generated elsewhere and almost without exception lose water to ground water throughout the desert sections of their courses. Estimated ground water recharge in arid and semiarid areas may be as much as 10 times more effective than direct infiltration of precipitation (9). Therefore, changes in surface water supplies caused by technology may have significant consequences for nearby or distant ground water supplies.

Ground Water Quality

Ground water-quality problems are not necessarily unique to arid or semiarid areas. However, some pollution problems may reach critical levels more quickly than in more humid areas because of the low recharge rates of drier areas.

Precipitation reaching the ground contains only minor amounts of dissolved mineral matter. The quantity and type of mineral matter dissolved by this precipitated water, once it reaches the ground, depend on the chemical composition and physical structure of the rock or soil on which it falls as well as on the physical and chemical properties of the precipitation (e.g., temperature, acidity). Carbon dioxide, sulfate, and other natural and human-introduced, acid-forming compounds derived from the atmosphere and from organic materials in the upper soil layers form weak acids in combination with water and assist the solvent action of the water as it moves downward.

Most "salts" (dissolved materials) are added to ground water as a result of soil and rock weathering (table 70). Excess irrigation water percolating to the water table may contribute substantial quantities of salt. Water passing through the root zone of cultivated areas usually contains salt concentrations several times that of the applied irrigation water. Increases result primarily from the evapotranspiration process, which tends to concentrate the salts in irrigation waters. In addition, fertilizers, pesticides, and selective absorption of salts by plants and soil minerals will modify salt concentrations of percolating waters. Factors governing the increase of dissolved salt content of percolating waters include soil permeability, soil chemistry, drainage facilities, amount of water applied, type of crop(s), and climate. High concentrations of dissolved substances may be found in soils and ground water of arid and semiarid climates, where leaching is not effective in diluting the solutions. Similarly, poorly drained areas, particularly basins having interior drainage, such as much of Nevada and western Utah, often contain high concentrations. In some areas, such as the southern portion of the Ogallala aquifer in Texas and Oklahoma, high salinity may be the result of the original sedimentary deposition of the rocks under saline or briny waters.

Many ground waters contain salts in such concentrations as to make them unusable for ordinary water-supply purposes. Federal drinking-water standards recommend that total dissolved solids not exceed 500 parts per million (ppm). Specific limits of permissible salt concentrations for irrigation waters cannot be so precisely stated because of the wide variations in salinity tolerance among different plants (ch. IX). In general, a salinity level of 1,000 ppm is considered a hazard for most irrigation purposes in the United States, although the extent to which such water can be used successfully will depend on the quality of the soils involved. A well-drained soil,in certain cases, may produce a crop even using high-salinity water, whereas a poorly drained soil may fail to produce a crop using water of a similar or better quality. Keeping in mind this variability, a ma-

Table 70.—Sources and Effects of Dissolved Materials in Ground Water

Constituent or physical property	Source or cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, usually 1 to 30 ppm[a]	Forms hard scale in pipes and boilers and on blades of steam turbines
Iron (Fe)	Dissolved from most rocks and soils; also derived from iron pipes. More than 1 or 2 ppm of soluble iron in surface water usually indicates acid wastes from mine drainage or other sources	On exposure to air, iron in ground water oxidizes to reddish-brown sediment. More than about 0.3 ppm stains laundry and utensils. Objectionable for food processing. Federal drinking-water standards state that iron and manganese together should not exceed 0.3 ppm. Larger quantities cause unpleasant taste and favor growth of iron bacteria
Calcium (Ca) and magnesium (Mg)	Dissolved from moist soils and rocks, but especially from limestone, dolomite, and gypsum	Cause most of the hardness and scale-forming properties of water. Waters low in calcium and magnesium are desired in electroplating, tanning, dyeing, and textile manufacturing
Sodium (Na) and potassium (K)	Dissolved from most rocks and soils	Large amounts, in combination with chloride, give a salty taste. Sodium salts may cause foaming in steam boilers, and a high sodium ratio may limit the use of water for irrigation
Bicarbonate (HCO) and carbonate (CO_2)	Action of carbon dioxide in water on carbonate rocks	Produce alkilinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot-water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium cause carbonate hardness
Sulfate (SO_2)	Dissolved from many rocks and soils	Sulfate in water containing calcium forms hard scale in steam boilers. Federal drinking-water standards recommend that the sulfate content not exceed 250 ppm
Chloride (Cl)	Dissolved from rocks and soils; present in sewage and found in large amounts in ancient brines, seawater, and industrial brines	In large amounts in combination with sodium gives salty taste. In large quantities increases the corrosiveness of water. Federal drinking-water standards recommend that the chloride content not exceed 250 ppm
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils, but includes organic matter	Federal drinking-water standards recommend that the dissolved solids not exceed 500 ppm. Waters containing more than 1,000 ppm dissolved solids are unsuitable for many purposes
Hardness as $CaCO_2$ calcium carbonate	In most water, nearly all the hardness is due to calcium and magnesium.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of that is called noncarbonate hardness
Acidity or alkalinity (hydrogen ion concentration, pH)	Acids, acid-generating salts, and free carbon dioxide lower pH. Carbonates, bicarbonates, hydroxides and phosphates, silicates, and borates raise pH.	A pH of 7.0 indicates neutrality in a solution. Values greater than 7.0 denote increasing alkalinity; values less than 7.0 indicate increasing acidity. Corrosiveness of water generally increases with decreasing pH
Dissolved oxygen (O_2	Dissolved in water from air and from oxygen given off in photosynthesis by aquatic plants.	Dissolved oxygen increases the palatability of water. Under average stream conditions, 4 ppm is usually necessary to maintain a varied fish fauna in good condition. For industrial uses, zero dissolved oxygen is desirable to inhibit corrosion

[a] ppm = parts per million.

SOURCE: Paul R. Ehrlich, Anne H. Ehrlich, and John P. Holdren, *Ecoscience: Population, Resources, Environment* (San Francisco: W. H. Freeman & Co., 1977). (Original source: Charles B. Hunt, *Physiography of the United States* (San Francisco, W. H. Freeman & Co., 1967).

jor factor affecting the suitability of ground water for irrigation increasingly will be the salinity level of the water (fig. 65).

"Hardness," another effect of the concentration of certain salts in water, also impacts on the suitability of water for irrigation. Hardness results from the presence or absence of compounds of calcium and magnesium. The U.S. Geological Survey (USGS) classifies hardness according to the amount of calcium carbonate or its equivalent that would be formed if the water were evaporated (table 71). "Hardness" varies across the Western United States (fig. 66).

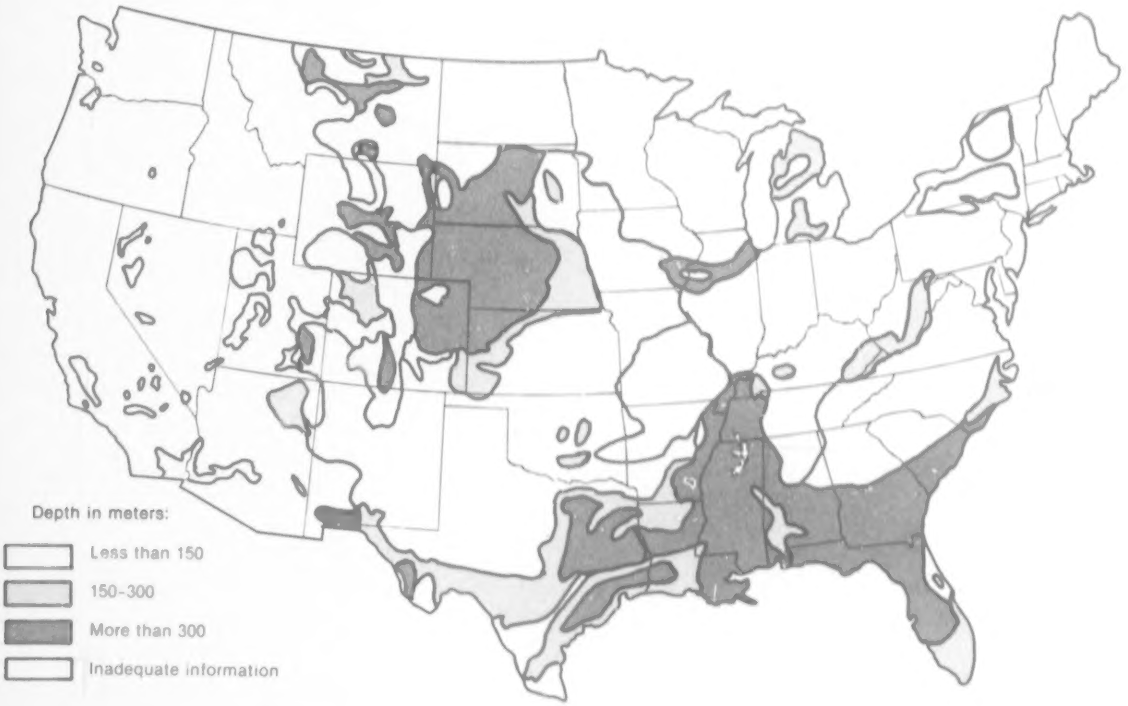
While hardness is an undesirable characteristic for many uses of water, some hardness is essential if soil quality is to be maintained. As water hardness decreases, the calcium and magnesium may be replaced by sodium, which will react with the soil and reduce its ability to transmit water. The Salinity Laboratory of the Department of Agriculture recommends the use of the Sodium Absorption Ratio (SAR) index, which measures the ratio of sodium to calcium and magnesium and can be directly related to the absorption of sodium by soil. Water containing as much as 40 percent sodium (relative to the concentration of calcium

Table 71.—Hardness Classification

Parts per million $CaCO_3$	Classification
0-60	Soft
61-120	Moderately hard
121-180	Hard
More than 180	Very hard

SOURCE: H. Baldwin and C. McGuinness, *A Primer on Ground Water*, U.S. Geological Survey, 1963.

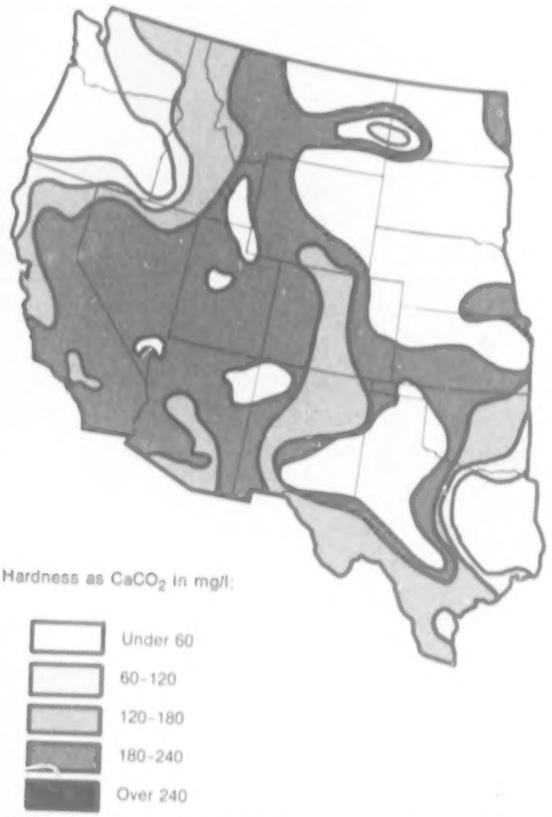
Figure 65.—Depths at Which Saline Ground Water Is Encountered



Saline water is defined here to contain more than 1,000 mg/l dissolved salts, a concentration that represents a high-salinity hazard for many irrigated crops.

SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980).

Figure 66.—The Hardness of Ground Water in the Western United States (areas shown represent average conditions)



SOURCE: D. Todd, *Ground Water Hydrology,* 2d ed. (New York: John Wiley & Sons, Inc., 1980).

and magnesium) is classified as "good" for irrigation uses, while values as high as 60 percent are "permissible." Sodium levels are generally low throughout the Western United States, at least in the shallow aquifers, with the exception of portions of the Texas-Gulf and Pacific Northwest regions (15). There is some indication that deeper aquifers of the northern Great Plains and interior basins of the Western region may occasionally have higher sodium levels that would render their use for irrigated agriculture undesirable.

Human activities may affect the quality of ground water in two major ways: 1) by accelerating the rate of buildup of compounds or components normally found in ground water, and 2) by adding or increasing the concentration of dissolved constituents during beneficial use of water. The first results from plowing fields or any similar action that expedites the normal movement of water into and through soils containing soluble compounds. The second results from discharging inorganic chemicals, biological agents, and organic compounds associated with municipal, industrial, and agricultural uses into the environment through which water may move. (These are discussed in detail in chapter IV.)*

Detection of ground water-quality degradation depends largely on the existence of monitoring wells. It is highly probable that some potential sources of ground water pollution in the Western United States are not located near a water-quality monitoring station. Knowledge of the geographical distribution of and contributions to ground water-quality degradation is incomplete. Many criticisms of the surface water-quality monitoring network contained in the General Accounting Office (GAO) (14) critique apply equally to the ground water-quality monitoring network. These include problems related to taking samples at fixed time intervals, which may not coincide with the presence of the pollutant, and the location of the monitoring well network, which may not coincide with the potential sources of pollution. Moreover, GAO identified problems related to field and laboratory inconsistencies in the collection and analysis of water samples and the types of data analyses used.

In addition, because the general flow of ground water is not directly observable but must be inferred from mathematical models, the geographical extent of any pollutant source is much more speculative than is the case with surface water. It can be assumed that the pollutants in surface waters in any given area will generally be present in the ground water, modified in some cases by filtering or by chemical interactions with the soil or aquifer constituents. A more detailed discussion of water quality and its associated public health aspects is presented in chapter IV.

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*Effects of acid rain are analyzed in the OTA assessment: *The Regional Implications of Transported Pollutants,* in press.

THE TECHNOLOGIES

Increasing Ground Water Supplies

Effective planning and management of ground water resources at a particular site must be based on the characteristics of the associated ground water region or basin within the region and on the interrelated nature of ground and surface water. Management objectives must take into account not only the geology and hydrology of the basin but also the economic, political, legal, and financial aspects of managing the water resource. Typically, optimum economic development of the water resources of an area requires an integrated approach that coordinates the use of both ground and surface water. Such development must consider both the quantity and quality of those resources to be successful.

With the exception of a decision not to extract ground water, most management technologies affecting water quantity may be considered active. They involve attempts to increase the recharge artificially to the aquifer above volumes that would occur under natural conditions. Technologies include water spreading and the use of recharge wells or pumping to induce recharge from natural surface water bodies. The choice of a given method, or combination of methods, is highly site-specific and will be governed by local topographic, geologic, climatic, and soil conditions; the quantity and quality of the water to be recharged; and the ultimate use for the water.

A fundamental requirement for artificial ground water recharge is that excess water be available, either locally or by import into a region, during all or part of each year. Without a supply of "excess" water during at least some portion of each year, artificial recharge technologies are not feasible. A number of areas exist in the Western United States that appear to have no water supply in excess of existing use patterns (ch. III). In some of these areas—for example, southern California and central Arizona—wastewater is increasingly used for ground water recharge. The implications of this practice for water quality are discussed below and in chapter IV.

Water Spreading

INTRODUCTION

Water spreading involves the construction of basins, pits, or barriers in or near natural stream channels to impound water and cause it to infiltrate the ground surface rather than leave the basin as surface runoff. This approach is most appropriate where the aquifer to be recharged is a near-surface, unconsolidated aquifer having few impermeable layers to impede either the vertical or horizontal flow of the water.

The typical ground-water recharge basin is excavated to a depth of 10 ft or more with side slopes as steep as the soil will allow when saturated. For some soils, special protection, such as broken rock, is required at the anticipated water surface to reduce wave erosion and the resultant turbidity in the water caused by bank erosion. Small check dams have been built in stream channels to impound surface runoff briefly and to increase the wetted surface area of the stream bed.

Experience in the operation of offstream ground-water recharge basins indicates that the surface area of the spreading basin is less important than the wetted perimeter. The bank area is the most important aspect of the wetted perimeter because falling sediment seems to clog this area less than on the bottom. The steeper the side slopes, the greater the recharge capability. The greater the perimeter of the basin, the more bank area available. Curvilinear basin sides provide a longer perimeter and result in a more esthetically pleasing facility in urban areas.

ASSESSMENT

No information is available on the extent of water spreading in the Western United States. Information is available for two areas in California, the Tulare Basin and southern California, where a total of 173 offstream basin and pit facilities were in operation as of 1973. These produced a total of approximately 892,000 acre-ft of recharge annually. This amount is an average of slightly more than 5,000 acre-ft per facility and represents 40 percent of the total recharge that was accomplished in the State of California during the 1972-73 water year (11).

For these two facilities, the average cost of operating and maintaining surface recharge basins was $6.00 to $8.50/acre-ft, plus capital costs (land acquisition and construction) of $1.25/acre-ft (1973 dollars). The use of a coagulant to reduce the turbidity* of the influent water increased the cost of operation by an additional $3.10/acre-ft. While these results are site-specific, they illustrate what can be accomplished in one area when recharge basin technology works and is used intensively.

The two primary limitations on the application of this technology are the availability of land and the availability of unappropriated surface water. In many areas of the Western United States, one or both of these will effectively make the technology impossible. A further limitation is the lack of a suitable geologic setting. Recharge basins and pits will work well only with a near-surface, unconfined aquifer or in the natural recharge area of the aquifer.

Recharge Wells

INTRODUCTION

A recharge well moves water from the surface to freshwater aquifers. Recharge wells are a way to increase ground water reserves where deep, confined aquifers must be recharged, or in urban areas, where land values preclude the development of water spreading.

Recent studies on the use and success of recharge wells are scarce. A few regions in the Western States have experience with this technology. At least 2,000 recharge wells are located in the agricultural lands of Idaho's Snake River plain (10). These wells are typically 2 to 3 ft in diameter and 20 to 30 ft deep, and are capable of accepting flows up to approximately 700,000 ft^3 (16 acre-ft) per day. The geology of the area consists of alternating layers of fractured and permeable basalt, a common volcanic rock. A study of the effect of these disposal wells on water quality revealed that ground water moved rapidly through fractures and channels in the basalt formations, that bacterial pollution persisted underground, and that suspended solids were reduced by downward percolation.

ASSESSMENT

In California, where artificial recharge is practiced most extensively of the Western States, recharge wells accounted for 12 percent of the recharge projects in 1959 but only 1 percent of the recharged water (8). Davis, et al. (2), present data showing an annual recharge of approximately 1,100 acre-ft/yr for a single well in the San Joaquin Valley, but stress the lack of experimental data. Todd (10) gives average values ranging from 200 to 400 acre-ft/yr for six sites in southern California and points out that the highest rates will occur in highly porous rock formations such as limestone and lavas.

According to USGS, recharge wells are ". . . justified only where the spreading method is not feasible" (1). Impermeable near-surface layers of rock or soil would render the spreading method geologically infeasible, while higher valued uses of land could render it economically infeasible.

For most aquifers, artificial recharge rates using recharge wells seldom equal pumping rates. The difficulty lies in the fact that pumping and recharging differ by more than just a simple change in direction. As water is pumped from a well, fine material present in the aquifer is carried through the coarser particles surrounding the well and into the well where it is removed with the extracted water. In the reverse direction, any silt carried into a recharge well will be filtered out by the coarser materials and will tend to clog the aquifer surrounding the well. Dissolved air carried to the aquifer by recharge water will similarly tend to clog the well. Bacteria, which will be a much more common constituent of recharge water than of natural ground water, can form growths on the well screen and the surrounding rock or soil, thereby reducing the effective recharge area of the well. The chemistry of the recharge water may not be in equilibrium with the aquifer or the natural ground water, thus producing chemical reactions that may reduce the permeability and porosity of the aquifer. In general, ground water recharge using wells will only be suitable for high-quality, treated water, and considerable experience is required to maintain optimum recharge rates. The recharge well is a technology that is limited to situations where there are no other options.

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*Water clouded with suspended sediments.

Improving Ground Water Quality

Introduction

In general, technologies to maintain or improve the quality of ground water are largely designed to prevent pollution. In most cases, once a ground water source has been polluted, it responds very poorly to attempts to restore its original quality.

Water reaches ground water levels by deep percolation from precipitation falling on the overlying land surface or through interconnected flow with surface water bodies (see ch. III). This recharge to ground water aquifers may be either artificial, as discussed above, inadvertent, or natural. Inadvertent recharge occurs as an unplanned result of some activity not designed specifically to recharge the ground water artificially. Included in this category is water from irrigation, cesspools, septic tanks, broken water mains, sewers, landfills, waste-disposal facilities, canals, and reservoirs. Whatever the source of recharge, degradation of the ground water quality may occur if polluted water is introduced. Once it has occurred, ground water pollution may be more difficult to detect than surface water pollution because of the relative inaccessibility of the water. Also, depending on the pollutant and the natural filtering by the aquifer materials, the subsurface pollution may be more difficult to control than surface water pollution, and it may move within the aquifer and persist for decades.

Technologies to improve ground water must be designed for a specific water-quality problem at a specific site. Their success will be determined by the extent to which the local geology, ground water movement, and nature of the contaminant are considered. All waters contain some amount of either dissolved or suspended contaminants. Technologies associated with ground water pollution must be focused largely on preventing pollutants from entering the ground water system. The sources of these pollutants are diverse and the list of potential pollutants is extensive, as discussed earlier in this chapter and in chapter IV.

One form of ground water pollution that sometimes may be dealt with technologically involves the intrusion of seawater into coastal aquifers. Seawater intrusion initially occurs when the coastal aquifer is pumped beyond its natural freshwater recharge capacity ("mined") or when freshwater recharge decreases naturally. In either case, seawater displaces or mixes with the freshwater in the aquifer. As little as 2 percent of seawater in an aquifer can render the water unpotable. In the coastal section of Texas and portions of California, for example, this problem already exists to varying degrees (15). The primary technologies for controlling saline water intrusion are:

1. Modification of pumping patterns, which typically involves construction of new wells at a site further inland.
2. Artificial recharge to balance withdrawals. This normally involves development of a supplemental water source.
3. Extraction barriers (a line of pumping wells along the coastal line), which create a trough in the water table into which the seawater flows. This water is then lifted to the surface and subsequently discharged back into the sea.
4. Injection barriers (a line of recharge wells along the coastal line), which create a "ridge" of freshwater beyond which the higher density seawater cannot penetrate.

This normally involves development of a supplemental water source.

Assessment

All technologies designed to improve ground water quality must be assessed in terms of:

- whether the contamination exists at a concentration sufficient to cause problems for the intended water use,
- the source of the ground water contamination, and
- the nature of the hydrogeologic environment.

The combinations and severity of impacts are complex, and in many cases largely undefined, in view of the current state of knowledge about ground-water flow regimes and the behavior of contaminants at a particular site.

Pollution potential is largely dependent on whether the recharge to ground water is taking place above or below the water table. Elimination above the water table (e.g., by soil filtering, biological decomposition, chemical deposition) may be effective for some pollutants, generally organics. The exceptions are the major inorganic constituents, many organic pesticides, and viruses. As the types and volumes of contaminants being introduced into the ground water system increase, the traditional dependence on the soil as a filtering agent becomes less feasible. Many organic chemicals pass through the soil virtually unchanged and viruses may be unaffected by soil filtering. Thus, many of the contaminants now being introduced into the ground water system are effectively permanent for purposes of society's planning horizon.

The most problematical aspect of ground water pollution involves the duration of the decreased water quality and the most effective form of water-quality treatment. In this regard,

> An important aspect of ground water pollution is the fact that it may persist underground for years, decades, or even centuries. This is in marked contrast to surface water pollution. Reclaiming polluted ground water is usually much more difficult, time consuming, and expensive than reclaiming polluted surface water. Underground pollution control is achieved primarily by the pollution source, and secondarily by physically entrapping and, when feasible, removing the polluted water from the underground (10).

In light of this technological limit, the management of ground water quality involves managing the potential sources of ground water pollution and control *before* the pollutant is introduced into the ground water system instead of treating the pollution after it occurs. This is an extremely complex matter, largely involving adjustments in the ways in which waterborne wastes are disposed rather than the technological means of purifying water once it is contaminated. With modifications, the technologies for controlling seawater intrusions into freshwater aquifers may be applied to the removal or isolation of any contaminant.

Improving Ground Water Withdrawal Efficiency

Introduction

An important consequence of the reliance on ground water for irrigated agriculture pumping has been the increased cost of obtaining water from this source. In the 1960's and early 1970's, when the rate of withdrawal and overdraft were rising rapidly, concerns grew about the effects of pumping on the long-term availability of ground water for irrigation. More recently, the fear of depletion has been displaced by the much more immediate concern that energy prices will make irrigation with ground water uneconomical in some areas, even with much of the water still in the aquifer.

Increasingly, when water must be lifted several hundred feet, energy costs tend to be the major component of water costs. The energy costs of pumping 1 acre-ft of water from various depths with alternative fuels as well as fuel prices have increased greatly for some areas in the last 10 years, and further increases are projected (table 72).

Assessment

Technologies to improve the efficiency with which ground water can be pumped from

Table 72.—Energy Costs for Pumping Ground Water (1977 constant dollars)

These costs are for pumping 1 acre-ft of ground water from various depths with alternative fuels and fuel prices for 1970-2000.

Fuel	Pump lift (ft)	Energy costs under alternative fuel prices 1970	1980	2000
Natural gas	100	$ 1.13	$ 4.56	$ 9.12
	200	2.30	9.29	18.58
	300	3.43	13.86	27.72
Electricity	100	7.52	8.88	17.76
	200	25.03	17.76	35.52
	300	22.55	26.64	53.28
LPG	100	7.32	12.60	26.20
	200	14.65	25.20	50.40
	300	21.98	37.80	75.59
Diesel	100	5.24	14.96	29.92
	200	10.59	30.00	60.00
	300	15.74	44.96	89.92

SOURCE: The technical assumptions such as the amount of fuel and the pressure required to lift an acre-foot of water are based on Gordon Sloggett, *Energy and U.S. Agriculture: Irrigation Pumping, 1974-77* (Washington, D.C.: U.S. Department of Agriculture, September 1979). Other assumptions include a 60-percent pumping efficiency. Fuel costs in 1977 constant dollars are: natural gas ($/mcf) 0.39 in 1970, 1.58 in 1980, and 3.15 in 2000; electricity ($/kWh), 0.033 in 1970, 0.039 in 1980, and 0.078 in 2000; LPG ($/gal) 0.25 in 1970, 0.43 in 1980, and 0.86 in 2000; diesel ($/gal) 0.28 in 1970, 0.80 in 1980, and 1.60 in 2000. The 1970 prices for LPG, and diesel are a national average obtained from *Agricultural Prices, Annual Summary* (Washington, D.C.: U.S. Department of Agriculture, June 1977). The 1970 prices for electricity are a national average obtained from *Agricultural Prices*, October 1977. The 1970 price for natural gas was obtained by personal communications with Delbert Schwab, OSU. The 1980 prices reflect average prices paid by farmers in Nebraska, Kansas, Oklahoma, and Texas in January 1980. The prices were obtained through phone conversations with officials in those states. Hans Landsberg, project director and co-authors *(Energy: The Next Twenty Years*, Cambridge, Mass., Ballinger, 1979, p. 71) conclude that, on average, real fuel prices will double by the year 2000. Although long-term contracts consummated in the last several years suggest natural gas prices may rise faster than the prices of the other three fuels, we have chosen to illustrate the implications of a doubling of all fuel prices rather than attempt to estimate differential rates of increase.

SOURCE: K. Frederick, and J. Hanson, *Water for Western Agriculture* (Washington, D.C.: Resources for the Future, 1982).

underground aquifers are necessary to compensate for rising energy costs and declining water levels. In addition to changing the spacing and depth of wells drilled into the aquifer, the technologies involved are generally concerned with the type of pump employed and the fuel or energy source used to drive the pump. Technologies for improving the efficiency of the water well itself also may be important in certain cases.

IMPROVING PUMPING-SYSTEM EFFICIENCY

Pumping efficiency is the ratio of the theoretical to the actual energy input needed for a given water output. It is essentially the product of the efficiencies of the pump and the power unit. A new pump should have an efficiency of about 75 percent when properly installed. Internal combustion engines often reduce the efficiency of the pumping system by another 5 percent because of the gearhead. The power-system efficiency varies widely with engine type. Reasonable engine efficiencies are 90 percent for electric, 24 percent for natural gas, and 32 percent for diesel fuel. Overall attainable efficiencies for pumping systems are about 66 percent for electric, 17 percent for natural gas, and 20 percent for diesel (6).

Inefficient pumping systems result in unnecessarily high pumping costs. Recent tests by the High Plains Underground Water Conservation District No. 1 in Texas showed that some farmers pay twice or even three times as much for irrigation because of the sizing, staging, and condition of the pump. Oversized pumps, specifically, were a major source of inefficiency. Commonly, the pumps had been designed years earlier to handle larger quantities of water than the well could currently yield (because of lowered water tables). Other sources of energy loss included improper staging to accommodate changes in water levels or additional lift requirements of newly installed sprinkler systems and reliance on worn pumps. The condition of the power unit, especially with natural gas internal combustion engines, was occasionally the source of some inefficiency, but those problems were not so severe as those involving the pumps.

Pump efficiency has a large effect on the cost of pumping water. According to calculations by Frederick and Hanson (table 73), energy costs may rise as much as 40 percent as the pump efficiency declines from 70 to 50 percent, and costs may rise another 67 percent with a decline to 30-percent efficiency. At 1980 energy costs (deflated to 1977 constant dollars), a decline in pump efficiency to 50 percent costs a farmer an additional $3.19/acre-ft with electricity compared to the costs of a 70-percent efficient well.

The type of fuel is as important as the pumping depth in determining a farmer's energy costs. Despite a fourfold rise in price since

Table 73.—The Effect of Pumping Efficiency on Pumping Costs (1977 constant dollars)

Energy costs to pump 1 acre-ft of ground water 200 ft with alternative fuels, fuel prices, and pump efficiencies.

Fuel	Pump efficiency	Fuel price		
		1970	1980	2000
Natural gas	70	$ 1.97	$ 7.96	$15.93
	50	2.76	11.15	22.30
	30	4.60	18.58	37.16
Electricity	70	12.88	15.22	30.45
	50	18.04	21.31	42.62
	30	30.06	35.52	71.04
LPG	70	12.56	21.60	43.20
	50	17.58	30.24	60.48
	30	29.30	50.40	100.80
Diesel	70	9.08	25.71	51.43
	50	12.71	36.00	72.00
	30	21.18	60.00	120.00

SOURCE: K. Frederick and J. Hanson, *Water for Western Agriculture* (Washington, D.C.: Resources for the Future, 1982).

1970, natural gas continues to be the least expensive means of pumping (table 74). In 1980, natural gas was only half as expensive as electricity, the next least expensive source of energy. Diesel, as a result of rapid price increases in the last 2 years, is now the most expensive fuel.

Electricity accounts for 50 percent of the irrigated acreage served by onfarm pumps, and within the Pacific region virtually all irrigation pumps are electric (table 74). Abundant hydropower is the least expensive fuel in the Pacific Northwest. Electricity is the most important fuel in the Mountain States (74 percent) and accounts for substantial acreage in the Plains States (25 percent). Despite the 15-percent growth in electricity use between 1974 and 1977, expansion has been hindered because many electric utilities are near capacity and unwilling to add new irrigation customers because of peak load problems. One option for such cases might be to limit new customers to pumping during nonpeak hours.

The most rapid growth has been for diesel fuel, which increased by 723 percent between 1974 and 1977. Almost all of this growth came in the northern plains, the only area that uses substantial amounts of this fuel. Under the 1980 fuel costs listed in table 73, little further growth in diesel use is expected. Diesel fuel prices have jumped dramatically since 1978, and supplies have been erratic, especially at vital periods in the growing season.

Use of liquefied petroleum gas (LPG) has been concentrated in the Plains States. Although its use declined from 1974 to 1977, prospects for increased LPG use are good largely because of the supply or price problems with the alternatives. LPG prices have not risen like either diesel or natural gas (table 74), and in late 1979 there was a world surplus of LPG.

IMPROVING WELL EFFICIENCY

A water well is a hole or shaft, usually vertical, drilled or excavated in the earth to bring ground water to the surface. Many methods exist for constructing wells. Selection of a particular method depends on the purpose of the well, the quantity of water required, depth to ground water, geologic conditions, and economic factors. Shallow wells in unconsolidated aquifers, such as sand or gravel, may be dug by hand or machine, bored with an auger or constructed by driving a perforated pipe into the material. Deeper wells, or those completed in consolidated rocks, must be drilled using a cable tool or rotary drill.

Table 74.—Fuels Used for Irrigation (1,000 acres)

Region	Electricity		Diesel		Natural gas		LPG	
	1974	1977	1974	1977	1974	1977	1974	1977
Northern Great Plains	1,573	2,612	1,543	2,914	2,430	3,231	1,553	1,008
Southern Great Plains	2,007	2,347	151	166	6,742	6,949	509	568
Mountain	4,297	4,500	307	350	1,152	1,104	184	136
Pacific	6,197	6,717	4	9	84	31	0	0
17 Western States	14,074	16,176	2,005	3,439	10,409	11,315	2,246	1,712

SOURCE: K. Frederick and J. Hanson, *Water for Western Agriculture* (Washington, D.C.: Resources for the Future, 1982). (Original source: Gordon Sloggett, *Energy and U.S. Agriculture: Irrigation Pumping, 1974-77*, AER Report No. 436 (Washington, D.C.: U.S. Department of Agriculture, September 1979).

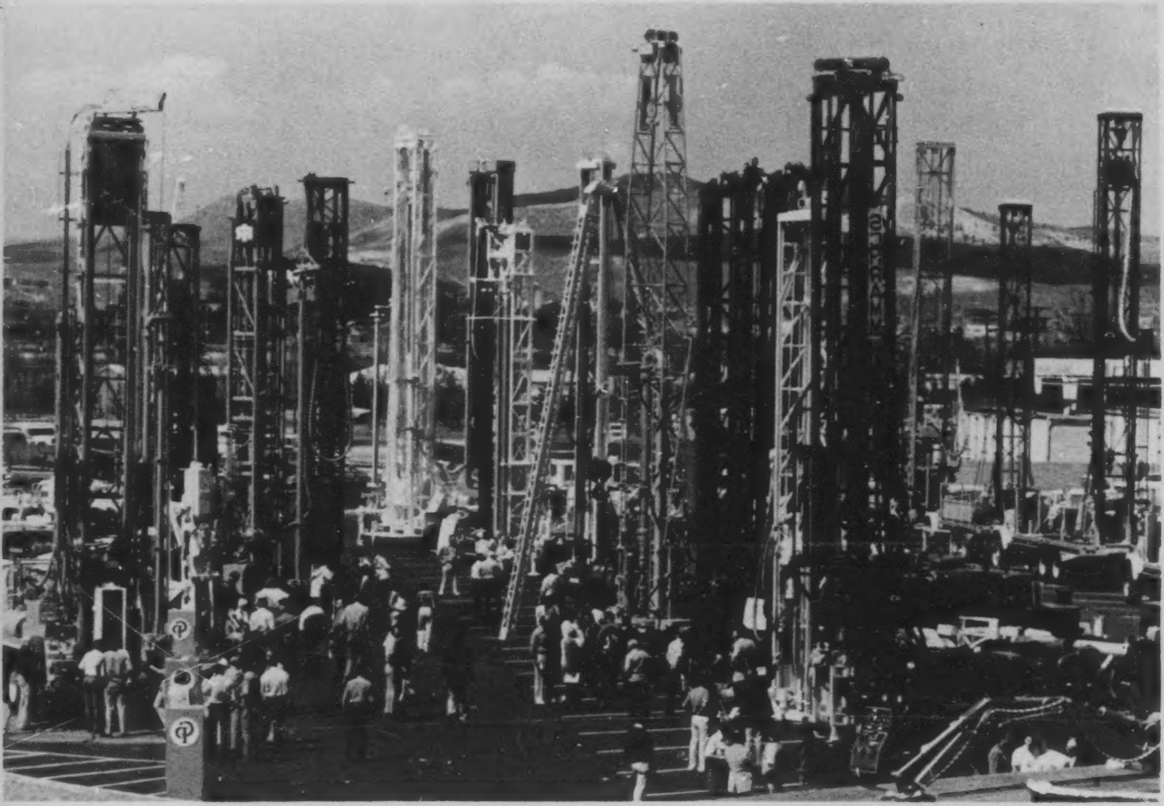


Photo credit: ©Ted Spiegel, 1982

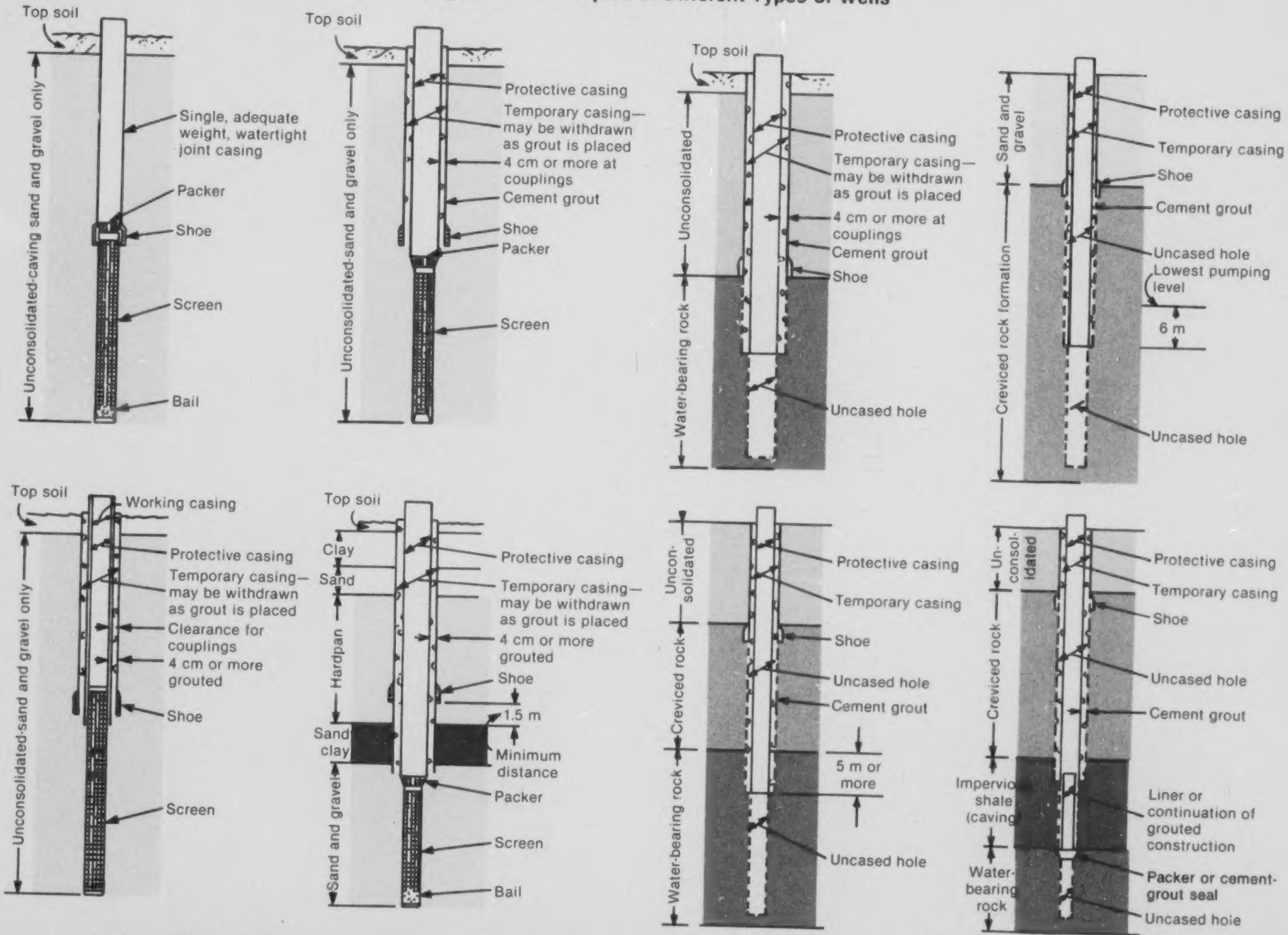
Drillers inspect a forest of the latest waterwell drilling rigs at the Pacific Northwest Exposition of the American Waterwell Association in Reno, Nev.

After a well has been drilled, it must be completed. This can involve the placement of casing, cementing of casing, placement of well screens, and gravel packing (fig. 67). These steps are necessary to ensure the stability of the well walls and to maintain a flow of water into the well through unconsolidated materials. Wells in consolidated rocks can often be left as open holes so that these completion techniques may not be required.

A new well, properly drilled, cased, and developed, should give years of satisfactory service with little attention. Many wells fail, however. They yield less water with time, a situation possibly associated with declining water tables. Yield decreases may also be a result of a faulty pump or poor well-construction techniques. Where the well is a factor, technologies exist that may be used to remedy the problem.

Problems associated with a declining water supply can sometimes be remedied by deepening the well. Where the problem in reduced yields is faulty well construction that involves poor casing connections, improper perforations of the casing, improper screens, incomplete placement of gravel packs, and poorly seated wells, repairs may be possible. Repairs to a well with one of these construction prob-

Figure 67.—Examples of Different Types of Wells


Top soil
Unconsolidated-caving sand and gravel only
Single, adequate weight, watertight joint casing
Packer
Shoe
Screen
Bail
Top soil
Unconsolidated-sand and gravel only
Protective casing
Temporary casing—may be withdrawn as grout is placed
4 cm or more at couplings
Cement grout
Shoe
Packer
Screen
Top soil
Unconsolidated
Water-bearing rock
Protective casing
Temporary casing—may be withdrawn as grout is placed
4 cm or more at couplings
Cement grout
Shoe
Uncased hole
Sand and gravel
Creviced rock formation
Protective casing
Temporary casing
Shoe
Cement grout
Uncased hole
Lowest pumping level
6 m
Uncased hole
Top soil
Working casing
Unconsolidated-sand and gravel only
Protective casing
Temporary casing—may be withdrawn as grout is placed
Clearance for couplings
4 cm or more grouted
Shoe
Screen
Top soil
Clay
Sand
Hardpan
Sand clay
Sand and gravel
Protective casing
Temporary casing—may be withdrawn as grout is placed
4 cm or more grouted
Shoe
1.5 m
Minimum distance
Packer
Screen
Bail
Uncon-solidated
Creviced rock
Water-bearing rock
Protective casing
Temporary casing
Shoe
Uncased hole
Cement grout
5 m or more
Uncased hole
Un-consol-idated
Creviced rock
Impervio shale (caving
Water-bearing rock
Protective casing
Temporary casing
Shoe
Uncased hole
Cement grout
Liner or continuation of grouted construction
Packer or cement-grout seal
Uncased hole

A. Examples of well construction in unconsolidated formations

SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980).

B. Examples of well construction in consolidated formations lems may cost $8 to $12/ft (estimated), whereas constructing a new well would cost an average of $25/ft (estimated) (4).

The third and most prevalent cause of well failure results from corrosion or incrustation of well screens. These problems are caused by chemical reactions between the well-casing materials and the ground water or by precipitation of materials carried in solution by the ground water. Screens can be cleaned by shooting a string of vibratory explosives in the well or by adding hydrochloric acid to the well to dissolve the incrustation, followed by pumping to agitate and surge the water in the well. Where slime-forming organisms block screens, particularly in recharge wells, treatment with chlorine gas or hypochlorite solutions can remedy the problem. For improving yields of wells drilled in solid rock, concentrated acid solutions or shooting with explosives is often effective.

LIMITS OF TECHNOLOGIES RELATED TO GROUND WATER

Special Characteristics of Ground Water

Ground water has certain characteristics that make its manipulation in any predictable fashion a difficult task. As part of the hydrologic cycle, ground water cannot be managed separately. Any management scheme must recognize that it is inextricably linked to the surface water resources of a region. Those regions that have overcommitted their surface water resources, either from the quantity or quality standpoint, cannot depend on a supply of "new" water from ground water supplies. Where surface water supplies are in short supply, it is likely renewable ground water supplies will also be in short supply. Similarly, in the Western United States, those areas with surface water supplies in excess of present requirements have ground water supplies that appear to be recharging naturally at rates at least equal to withdrawal.

Ground water is more diffuse than surface water. Legal and social practices in the past have generally treated ground water as if it existed in discrete underground bodies or streams. In fact, it is widely and unevenly distributed throughout most of the surface rocks of any given region. This characteristic means that the economic costs of ground water development for benefits received will be much higher than for development of the more concentrated surface water bodies.

Technologies designed to affect either the availability or quality of ground water generally must be applied at individual water wells. Thus, they are much more site-specific than are most other water-related technologies discussed in this assessment. This creates a number of unique problems in assessing the nature and degree of potential threats to the resource. Considerable information concerning local geology, recharge conditions, type of well construction, and the well's intended use is required before these technologies can be used with confidence. Discussion of problems involving more than a single water well involves the extrapolation of well data, using assumptions concerning variations in geology, climate, and other environmental controls. While there will generally be less disagreement among hydrogeologists concerning some of these assumptions and extrapolation techniques, the nonhydrologist may often be at a loss to assess the conclusions accurately.

Complex ground water models have been developed over the past two decades to aid in the evaluation of ground water problems.* However, the use of these models has been restricted to a limited number of specialists. For the most part, ground water information is anecdotal and deals with such local problems as ground water decline, water-quality deterioration, and land subsidence as a result of the

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*For an evaluation of methodologies, see the OTA assessment: *Use of Models for Water Resources Management, Planning, and Policy*, 1982.

overuse of ground water. Future management of ground water resources probably will involve the use of such computer simulation models because the behavior of the resource is so complex. This will require the development of a data-collection network for each application site that is much more extensive than that which now generally exists. Data collection and monitoring is a complex process that will strain the economic resources of most communities. It also requires a level of expertise that is rare at levels below that of State or Federal agencies.

Effects of Ground Water Overdrafting

Prolonged ground water overdrafting may lead to one or more undesired results. These include:

- progressive reduction in the total volume of the available ground and surface water supply, since these supplies are connected,
- development of uneconomic pumping conditions as depths increase,
- degradation of ground water quality,
- interference with other water rights as drawdown affects other parts of the aquifer, and
- land subsidence caused by lowered ground water levels.

The technologies to compensate for these effects are limited. There are no known technologies, for example, to recover water storage space lost by land subsidence or to improve degraded water in aquifers.

It is estimated that ground water overdrafting is occurring in each of the nine major water resources regions of the Western United States (15) (table 75, fig. 68). The extent of this overdrafting, and the ability of affected aquifers to recover in a reasonable time period if present demands are diminished varies widely among these regions. This variation results from the highly complex and variable geology and climate of the region. As early as 1949, Warne "... drew attention to 'trouble spots' throughout the United States where heavy draft upon the water-bearing formations has resulted in the depletion of the underground water at a rapid rate." According to Warne, in 1949 these areas of concern already included "the Central Valley of California, the West Basin southwest of Los Angeles, the High Plains of Texas, south of Amarillo . . . and elsewhere" (3). States where ground water withdrawals are a high percentage of total water use, it can be assumed that problems of sustainability will develop with time.

By definition, ground water overdrafting is nonsustainable, since the water resource is being used at a rate greater than it becomes available. According to the WRC estimates of ground water supply and use in the Western United States, the present (1975) ground water overdraft represents 12 percent of the total water withdrawn from all sources in the Western region and is some 20 million acre-ft annually (15). This is almost 1½ times the annual flow of the Colorado River.

Serious social disruptions may result when economic, social, or environmental systems develop, based on a limited surface/ground water supply. Arguments in favor of ground water mining are commonly economic in nature. It is argued that water in storage is of no value unless it is withdrawn. This argument is valid only to the extent that an infrastructure is not developed based on the limited supplies. As ground water supplies are depleted, surface water supplies commonly also become less available. Ground water becomes increasingly expensive to withdraw as water table levels decline. Ultimately, water must be imported in order to support the water-dependent infrastructure. As economic costs make this increasingly unfeasible, however, those areas may suffer some economic decline.

Two recent examples of this sequence are the Central Arizona Project (CAP) and the Central Valley Project (CVP) in California. A GAO report estimated that the total cost for these two projects, designed to replace water originally mined from local aquifers, would be approximately $5 billion* (1977 dollars) (13). The

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*$1.5 billion for CAP and $3.5 billion for CVP.

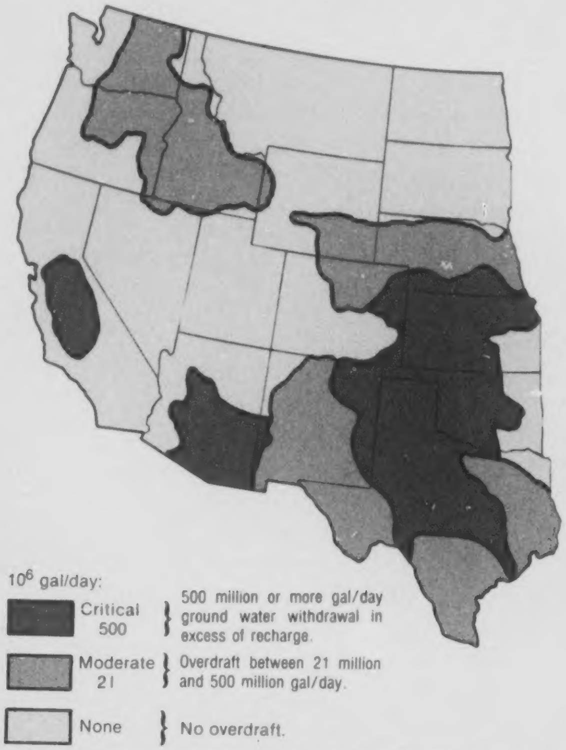
Table 75.—Ground Water Mining in the Western United States

The pressure on total water resources of a region increase as the percentage of ground water mining increases.

Region number	Subregion number	Name	Ground water mining as a percentage of annual offstream consumption
10		MISSOURI	17
	03	Missouri-Musselshell	1
	05	Western Dakotas	2
	06	Eastern Dakotas	7
	07	North and South Platte	13
	08	Niobrara-Platte-Loup	13
	09	Middle Missouri	16
	10	Kansas	41
	11	Lower Missouri	5
11		ARKANSAS-WHITE-RED	68
	01	Upper White	2
	02	Upper Arkansas	3
	03	Arkansas-Cimmaron[b]	100
	04	Lower Arkansas	2
	05	Canadian	85
	06	Red-Washita	55
	07	Red-Sulphur	1
12		TEXAS-GULF	50
	01	Sabine-Neches	8
	02	Trinity-Galveston Bay	19
	03	Brazos	78
	04	Colorado (Texas)	38
	05	Nueces-Texas Coastal	26
13		RIO GRANDE	16
	02	Middle Rio Grande	21
	03	Rio Grande-Pecos	46
	04	Upper Pecos	16
	05	Lower Rio Grande	1
15		LOWER COLORADO	53
	01	Little Colorado	7
	02	Lower Colorado Main Stem	27
	03	Gila	61
16		GREAT BASIN	16
	01	Bear-Great Salt Lake	3
	02	Sevier Lake	60
	03	Humboldt-Tonopah Desert	27
	04	Central Lahontan	3
17		PACIFIC NORTHWEST	5
	01	Clark Fork-Kootenai	2
	02	Upper/Middle Columbia	8
	03	Upper/Central Snake	4
	04	Lower Snake	7
	05	Coast-Lower Columbia	2
	07	Oregon Closed Basin	2
18		CALIFORNIA	8
	02	Sacramento-Lahontan	4
	03	San Joaquin-Tulare	10
	05	Central California Coast	10
	06	Southern California	8
	07	Lahontan-South	43

SOURCE: K. Frederick and J. Hanson, *Water for Western Agriculture* (Washington, D.C.: Resources for the Future, 1982). (Original source: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978), vol. 3, app. II, table II-6.

Figure 68.—Regions of Ground Water Withdrawal in Excess of Recharge


10^6 gal/day:
Critical 500
500 million or more gal/day ground water withdrawal in excess of recharge.
Moderate 21
Overdraft between 21 million and 500 million gal/day.
None
No overdraft.

SOURCE: J. Bredehoeft, "Physical Limitations on Water Resources in the Arid West," paper presented at: Impacts of Limited Water for Agriculture in the Arid West, Asilomar, Calif., Department of Land, Air, and Water Resources, University of California, Davis, 1982.

federally supported CAP will include the construction of canals to carry water from the Colorado River to the cities of Tucson and Phoenix, Ariz. The federally supported CVP is a large multipurpose project in California, consisting of 19 dams and related water conveyance systems and hydroelectric generating plants. The CVP's primary purpose is to provide irrigation water to the Sacramento and San Joaquin Valleys. According to the GAO Comptroller General:

> . . . it appears that the population and economies of the areas (Arizona and California) developed at higher rate than could be supported by the existing water supply. Once such developments had taken place, crisis-oriented solutions had to be considered which involved large expenditures and which required Federal assistance.

According to a recent study by Resources for the Future* (4) ground water mining has two adverse effects on water costs. First is the increased pumping lift. On a regional or statewide basis, this increase may average not more than 1 to 3 ft a year, generally signifying an annual increase of 1 or 2 percent. On a farm-by-farm basis, however, there is a great deal of variation, and an individual irrigator may face a more rapidly declining water level.

A second effect is the decrease in saturated thickness as the aquifer is mined. As saturated thickness declines, so does well yield. Eventually, additional wells and pumps are needed to maintain the flow. For example, a center-pivot distribution system requires a minimum well yield of 600 gallons per minute (gpm).

At lower yields, farmers must either adopt a new irrigation system requiring fewer gallons per minute, add to the number of wells, or be satisfied with less than optimum coverage. These alternatives tend to increase production costs or decrease crop yields. In Texas, where declines in saturated thickness are especially serious, some farmers have installed eight or nine smaller pumps, each yielding 75 to 150 gpm, to reach adequate output. On farms with a center pivot or other sprinkler system, the decline in the aquifer's saturated thickness and its resulting problems may have a greater impact on water costs than do the increased energy costs resulting from greater pumping lifts.

In addition to other effects, subsidence** is often associated with ground water mining. As the ground water level drops, the bouyancy provided by the water is removed and the individual grains in unconsolidated aquifers move closer together, diminishing the ability of the aquifer to store water and causing the overlying land surface to sink. While there are a number of land use activities that may cause this phenomenon, in the Western United States ground water mining associated with irrigated agriculture has produced the bulk of the existing land subsidence problems.

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*An independent, nonprofit economic analysis organization.

**The sink or collapse of the land surfaces.

The effects of subsidence on agriculture have been most extensive in those areas where ground water withdrawal for irrigation is common. For example, water withdrawal in the San Joaquin Valley of California produced subsidence of up to 20 ft by 1967 over an area of 2,500 square miles during 40 years. The gradual lowering of the land surface damaged expensive water-well casings, irrigation systems, buildings, and drainage and flood-control structures, and produced flow direction reversals in irrigation canals. In California's San Jacinto Valley, approximately 5,400 square miles of cropland have subsided at a rate of up to 1.2 ft/per year since measurements began in 1935. In some portions of the Valley, it has reached a total of 28 ft (12). Costs are high for repairing such damage. In California's Santa Clara Valley, subsidence costs during the same period were estimated at $15 million to $20 million.

A similar situation exists in the Texas-Gulf aquifers, where water withdrawals have been primarily for industrial and urban uses. Agricultural lands have been adversely affected by the resulting subsidence. During a 26-year period, 1943 to 1969, in the Houston area, a region some 15 miles in diameter suffered a 2-ft lowering of the surface. An area of about 60 miles, much of it rural land, suffered at least 6 inches of subsidence during the same period. These depressed land surfaces act as closed basins during heavy, hurricane-associated rainfall and thus periodically limit the land's usefulness for crop production.

CONCLUSIONS

Ground water use in the Western United States almost tripled between 1950 and 1975, and the percentage of the total water withdrawn in the region nearly doubled. Much of this increase has been made possible by technologies that have permitted the overdraft, or "mining," of ground water, leading to the noticeable depletion of the resource in many areas. Attempts to recharge these ground water supplies artificially depend on a water surplus during at least some part of each year to use for recharge. In many of the areas most affected by ground water overdraft, the *total* available renewable water resources are being completely consumed each year.

Water quality is highly variable among the major ground-water resource regions of the Western United States, varying with groundwater recharge rates, rock chemistry, and human waste-disposal practices. With the exception of portions of the Pacific Northwest and eastern Texas, the ground water of the Western States is moderate to very "hard," with high concentrations of calcium and magnesium salts. When water having high levels of these, or any other salts, is brought to the surface and used for irrigation, evaporation losses lead to increases of soil-salinity levels. Irrigation return flows, with high levels of dissolved salts and agricultural chemicals, percolate back into the ground water, producing a further deterioration of the existing water quality.

Once a ground water aquifer becomes contaminated, relatively little can be done to remove or contain the contaminant. A few technologies have been investigated for dealing with ground-water contamination problems, but in general these have been very expensive to implement and have produced uncertain results.* Technologies effective against ground water pollution are those associated with surface and subsurface waste disposal and designed to prevent contaminants from reaching the aquifer. Better control of toxic and noxious substances in surface and subsurface waters will probably remain the only feasible ground water pollution-control technologies in the foreseeable future.

While irrigated agriculture has consumed the largest volumes of ground water in recent dec-

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*OTA is currently conducting an assessment on ground water resources entitled: *Technologies To Measure, Monitor, and Mitigate Ground Water Contamination*, estimated delivery date late 1983.

ades in the Western United States, the percentage developed for municipal and industrial uses has become increasingly important. Many Western cities are now dependent on ground water. As ground water resources are degraded by ground water overdraft or quality largely caused by irrigated agriculture, the supplies on which these cities have become dependent also decline in both quantity and quality. While irrigated lands may be shifted to a use of lower value as water levels decline, cities cannot make this transition so easily. The social costs of declining water tables and increasing contamination of ground water resources of the Western United States must be addressed as both an agricultural and a broader social and public health problem. Until more understanding has been gained, the most appropriate ground water technology may be prudent and conservative water-use management.

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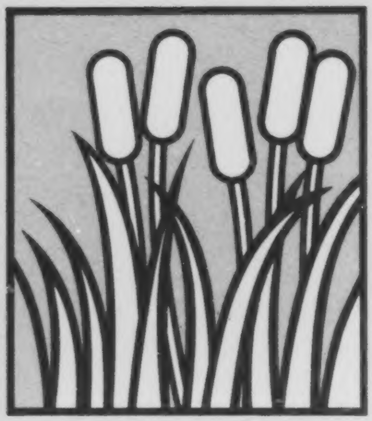

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Chapter XI

Selected Technologies Affecting Water and Land Management

Continued agricultural productivity of arid and semiarid lands will require more careful and integrated management of many resources, including water. Improved water and land management can help to restore the inherent productivity of many agricultural lands that suffer from erosion, soil compaction, soil salinity, or other adverse conditions. In irrigated areas, better water management may compensate for the decreasing availability of affordable water which many experts predict.

Management technologies rely on brainpower and there is no substitute for intelligent use of technology and "smart" users when resources become less available. This chapter highlights an assortment of these lesser known, and sometimes unconventional, practices for managing water and land. This discussion is not all-inclusive, however. Rather, each technology has shown its usefulness in some locations and may play an increasing role in arid and semiarid agriculture in the Western United States.

THE WATER SETTING

Most irrigation systems and arid/semiarid-land cropping systems developed to manage water; historically, patterns of agricultural land use and agricultural practices reflected this characteristic. Today, the more promising contemporary management schemes show a similar understanding of water in arid/semiarid lands: the limited absolute amounts of water, its spatial and temporal unevenness, its susceptibility to effective exhaustion, and the interconnected nature of different water resources. As an example, some areas are using the watershed (the fundamental hydrologic unit) as a political management unit. In other locations, individuals recognize that it is difficult to affect one hydrologic component without altering others and have linked the use of ground and surface waters.

The use and management of water, then, is becoming more attuned to economic and natural resource conditions. For some regions, however, the most precise use of water requires more careful land management rather than water management per se. Rangeland agriculture, for example, involves managing plants and animals to provide optimal production from existing precipitation. Although the amount of water involved is small compared to irrigated agriculture, the land areas are vast and agricultural production from these regions is significant nationally.

THE TECHNOLOGIES

Water Management

Flexible Cropping

INTRODUCTION

In much of the semiarid region, low precipitation limits dryland crop production to some type of crop-fallow (noncropping season) system. Traditionally, farmers in the low rainfall areas of the northern and central Great Plains have strictly practiced this alternate-year rotation. In the slightly higher rainfall regions of the southern Great Plains, more intense rotations such as two crops every 3 years or annual cropping have been possible.

Dryland farmers in recent years have practiced methods of crop production that improve water storage during the fallow period, such as stubble mulch tillage and conservation tillage (ch. VIII). These technologies have helped increase the amount of water stored during the fallow period. Although there have been tradeoffs, for example, in weed control, this higher level of soil water is sufficient in some cases to allow farmers to grow crops each year.

Flexible cropping is an outgrowth of this development. In this system, a crop is planted when stored soil water and predicted rainfall are favorable for a satisfactory yield. When

Box X.—"Best Management Practices"

The importance of management practices for achieving various resource objectives has been long recognized. Conservation plans initiated by the Soil Conservation Service during the 1930's, for example, recommended certain management practices for controlling soil erosion. "Best management practices" for controlling nonpoint sources of water pollution were formally recognized in the Federal Water Pollution Control Act (FWPCA) of 1972 (Public Law 92-500) as amended by the Clean Water Act of 1977. States were instructed to develop and implement "best management practices" to reduce this type of pollution. The actual "best" practices were not specified in the legislation nor in subsequent regulations issued by EPA.

USDA has remained involved with the original conservation plans as well as more recent programs. The Clean Water Act authorized USDA to provide technical and financial assistance to farmers and ranchers for adoption of FWPCA's best management practices. While the program has moved slowly, it has spurred recognition that combinations of practices applied at the watershed level are most likely to meet multiple objectives: water conservation, erosion control, clean air, sustained food and fiber production, wildlife habitat, and recreational lands.

Computerized agricultural models make the evaluation of management packages simple and effective. For example, the long-term effects of weather and the implementation of new tillage practices can be tested locally and regionally before investments are made. A variety of agricultural models are available for these and related purposes. These include: EPIC (Erosion Productivity Impact Calculation), CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), and SWAM (Small Watershed Model).

While technology exists for evaluating management practices, it has not been used to prepare integrated-management packages for farmers. Some people believe that an adoption bottleneck has resulted. Debate continues regarding who (i.e., public or private, Federal or non-Federal groups) should be responsible for putting together management packages. It is unlikely, however, that USDA's Agricultural Research Service (ARS) will assume major responsibility. The portion of the ARS budget allocated to integration of agricultural systems is expected to increase from 2 percent in 1982 to only 3 percent in 1990.

SOURCE: U.S. Department of Agriculture, Agricultural Research Service, "Agricultural Research Program Plan, 6-Year Implementation Plan, 1984-1990" (Washington, D.C.: U.S. Government Printing Office, 1983).

crop prospects are not favorable, no crop is planted, and a field is left fallow to store additional soil water.

ASSESSMENT

Flexible cropping systems were developed in the last few years for use in the northern Great Plains. Such systems have wide potential application throughout the Great Plains, but detailed procedures have yet to be developed for their use.

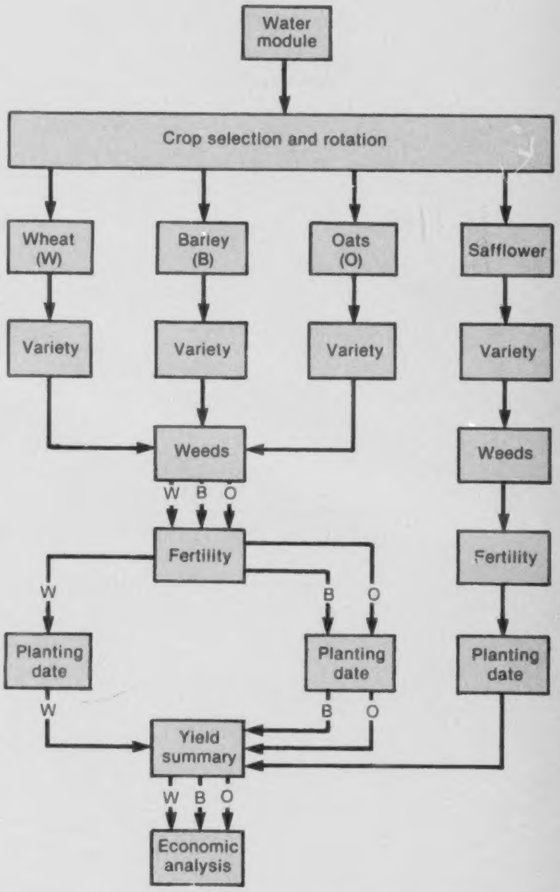
Success of a flexible cropping system requires a combination of preplanting, in-season, and postharvest practices. Before planting, a farmer assesses root-zone water-supply required for planting time and determines predicted seasonal precipitation for the growing season. Soil characteristics, crop-water requirements, and depth of rooting for different crops are also considered. If a farmer decides that soil moisture and predicted precipitation are sufficient, tillage operations are timed to maximize the water available to the crop. Fertilizer is applied to stimulate root growth during the growing season. Weed control and snow management are used after harvest to collect precipitation for the next growing season.

It is difficult for an individual farmer to evaluate all of these factors, and thus computerized management guides and users' manuals have been developed. In Montana, for example, these materials help farmers decide the best cropping and soil management options for wheat, barley, oats, and safflower based on stored soil water and expected growing season precipitation (figs. 69 and 70).

Besides making more systematic and optimal use of stored soil-water supplies and growing season precipitation, research indicates that the flexible cropping system may prevent the formation of saline seeps (ch. VIII), since soil water is used before it moves below the root zone.

Figure 69.—Crop-Management Model for Flexible Cropping

This model, developed in Montana, depicts grain yield as a function of water supply, crop, variety, weeds, fertility, planting date, and rotation. Management decisions and crop information are then provided to the user, who types responses to questions asked by the computer.



SOURCE: P. O. Kresge and A. D. Halvorson, *Flexcrop User's Manual: Computer-Assisted Dryland Crop Management*, Montana State University Cooperative Extension Service Bulletin 1214, Bozeman, Mont., 1979.

Many of the limitations associated with flexible cropping systems are similar to those experienced with other water-conservation technologies. For example, if plant-barrier systems are used to trap winter snow, weeds may increase. If conservation tillage is employed, managers may have difficulty seeding crops into the resultant residue. Where snow is collected, water might not filter properly into frozen soil.

Flexible cropping systems also have a unique set of management limitations. Crop rotations are a highly effective way to avoid weed, in-

Figure 70.—Sample Crop-Management Worksheet

Soil water

Moist soil depth (ft)[a]	Soil texture[a]	Weather location[a]	Date soil-water measured[a]

Crop information

Previous crop[a]	Crop to be grown[a]	Variety choice[b]	Variety code[a]

Weed information

Wild oat infestation[a]	Control[a]	Broadleaf infestation[a]	Control[a]

Fertility

NO_3-N to 4 feet lb/A[b,c]	N application rate lb/A[a,c]	Type of P soil test[b]	Soil test P[b]	P application rate lb/A[a,c]

Seeding date[a]

[a]Required for operation of program.
[b]Can be optional.
[c]lb/a = pounds per acre.

An illustration of the information needed for the flexible cropping model.

SOURCE: P. O. Kresge and A. D. Halvorson, *Flexcrop User's Manual: Computer-Assisted Dryland Crop Management*, Montana State University Cooperative Extension Service Bulletin 1214, Bozeman, Mont., 1979.

sect, and disease buildup, but they have become rare in many regions because of past economic constraints. Therefore, little information exists to guide farmers in choosing possible crop rotations. In addition, some crops* are difficult to work into a flexible cropping system because they are planted in the fall before most water is accumulated and total water supplies are known.

Also, social and economic considerations currently limit employment of flexible cropping systems. Farmers generally view flexible cropping as a riskier approach than traditional crop-fallow practices, one that requires a higher management commitment. Some farms may have the labor and time to conduct the intensive soil-water monitoring needed for its application, but total reliance on a flexible cropping system often requires resources (e.g., labor, capitol, and access to agricultural consultants who can assist in monitoring and planning operations) available most readily to large operations. Federal policies governing crop diversions and set-asides may pose a further barrier to adoption. For example, policies requiring farmers to reduce acreage in order to be eligible for certain benefits (e.g., commodity loans and disaster payments) may be in effect in years when soil-water conditions would allow full production. In other cases, set-asides may increase flexibility by allowing installation of soil- and water-conserving practices without losing a crop.

Irrigation Scheduling

INTRODUCTION

Traditionally, many growers schedule irrigation periods by examining crop appearance and soil-water conditions and judging future weather. Others time water applications by the calendar. Still others are forced to schedule irrigations by water delivery rotation systems. These scheduling procedures give generally satisfactory results but may not make the most efficient use of water, maximize crop yields, or save energy.

The concept of scientific irrigation scheduling* has received much attention in recent years. It takes into consideration:

- precipitation and evapotranspiration since the previous irrigation,
- allowable soil-water depletion at the particular growth stage of the crop, and
- expected precipitation and crop-water requirements before the next irrigation.

To assess the need for water application, two technically sophisticated methods are used: 1) environmental and plant monitoring, and 2) a water budget technique. In the first method, tensiometers, electrical resistance gypsum blocks, or neutron probes are used to measure soil water (ch. VIII). Plant water stress is inferred through use of infrared thermometers or pressure chambers. Some of these types of monitors do not indicate how much irrigation is needed.

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*For example, winter wheat.

*The prediction of the time and amount of water required for the next and future irrigations.

In the water budget method, an alternative to environmental monitoring, the crop root zone is visualized as a reservoir of available water. Water is withdrawn from the root zone through evaporation or drainage and added through rainfall and irrigation. If the volume of water in the root zone—the amount of water that can be drained without stressing the plant (or the allowable depletion)—and the depletion rate (or evapotranspiration) are known, the date of the next irrigation can be predicted. Coupled with accurate weather forecasts, this method allows for accurate irrigation scheduling.

ASSESSMENT

Irrigation scheduling services (ISS) are provided to about 1 million acres in the Western United States by Federal and State agencies and private consultants (13). Most services are based on computer predictions of time and amount of irrigation.

Several advantages of irrigation scheduling services have been noted by researchers. Limited information indicates that crop yields with irrigation scheduling can be increased by an average of 10 to 30 percent primarily a result of proper timing and sufficient water application although other research has been unable to document significant increases. Scheduling may reduce the number of irrigations per season by making maximum use of soil water and rainfall. It may also help to reduce pollution of ground water because less excess water is percolated through the soil. In areas where electricity is used for pumping irrigation water, irrigation scheduling may also help manage peak electrical loads. Moreover, because plant environmental conditions are better known, this technology permits managers to plan water rotations among fields, pesticide applications, tillage operations, and other activities to minimize crop stress and yield reductions.

A number of technical and social factors affect the adoption of irrigation scheduling. First, the effectiveness of the system depends on the total water application and measurement system, including delivery, application, and irrigation. Before scheduling can be implemented, each of these systems should be evaluated to determine capacity, needs, flexibility, and limitations. Surface water delivery systems to the farm in some areas are fixed and may not be adapted to scheduling techniques based on crop-water needs because of the short notice involved (ch. VII).

Second, field verification of computer predictions about environmental conditions is necessary because of site-specific variability in the depth of water applied at each irrigation, the crop rooting depth, soil water storage capacity, allowable depletions, effective rainfall, and crop evapotranspiration. These field checks require competent and trained personnel who can communicate effectively with growers. For example, the Bureau of Reclamation has developed an irrigation management service program to help irrigators schedule water deliveries and application. Private agricultural consultants have also developed scheduling services. These dual efforts raise questions about the government and private role in onfarm water management (19).

Third, irrigation scheduling services are adopted when definite economic benefits can be readily identified by the grower, since these services are costly and beyond the means of many farmers. Inexpensive and readily available water supplies reduce the incentive to implement scheduling. As discussed in chapter V, water law may often inhibit farmers from conserving irrigation water onsite since the water "saved" does not become available for other uses on the same farm. Again, the short-term economic incentive for adopting the technology may not be adequate, now, but this situation may change rapidly if water costs reflect more closely replacement value of water.

Fourth, there is general skepticism that yields can be improved by altering irrigation practices. Scheduling services can increase net income to growers to the extent that the level of

Box Y.—Water Management in Israel

Israel has limited freshwater supplies but a rapidly growing population. Consequently, water-management strategies during the 1980's have shifted from development of new supplies to management of water demand. Nationalized water resources, a national supply system, and elaborate programs of technical assistance to water users are important components of this approach. These arrangements were possible in part because Israel is a small country and neither farm groups nor water-rights holders existed to oppose their initiation.

Several methods are used to manage water demand: metering, pricing, and allocation. All water users are metered and receive annual licenses for ground water, runoff, and sewage effluents. Water prices are adjusted nationally, and larger water users pay higher prices. Water costs are high, reflecting the true scarcity of the resource. Each farm is allocated its water annually, an allocation which may be decreased the following year.

As a result of these policies, Israel is a leader in several water-use technologies. These include wastewater reuse, use of brackish water, and specialized irrigation systems. A close-working relationship between researchers and farmers has also ensured that research results are quickly adopted and often cooperative groups of farmers manufacture new instruments themselves.

SOURCE: U.S. Congress, Office of Technology Assessment, "Water and Agriculture in Arid Lands: Selected Foreign Experience—A Background Paper" (Washington, D.C.:U.S. Government Printing Office, OTA-BP-F-20, May 1983).

some production input is decreased, the quality of the crop is increased, or yields are increased. Among those who provide scheduling services, there may be an overemphasis on the degree to which yields can be improved or irrigation can be reduced.

In sum, irrigation scheduling is a necessary but incomplete management tool for increasing irrigation efficiencies. It can help to conserve water when precise control is available throughout the water distribution system.

Wastewater Reuse

INTRODUCTION

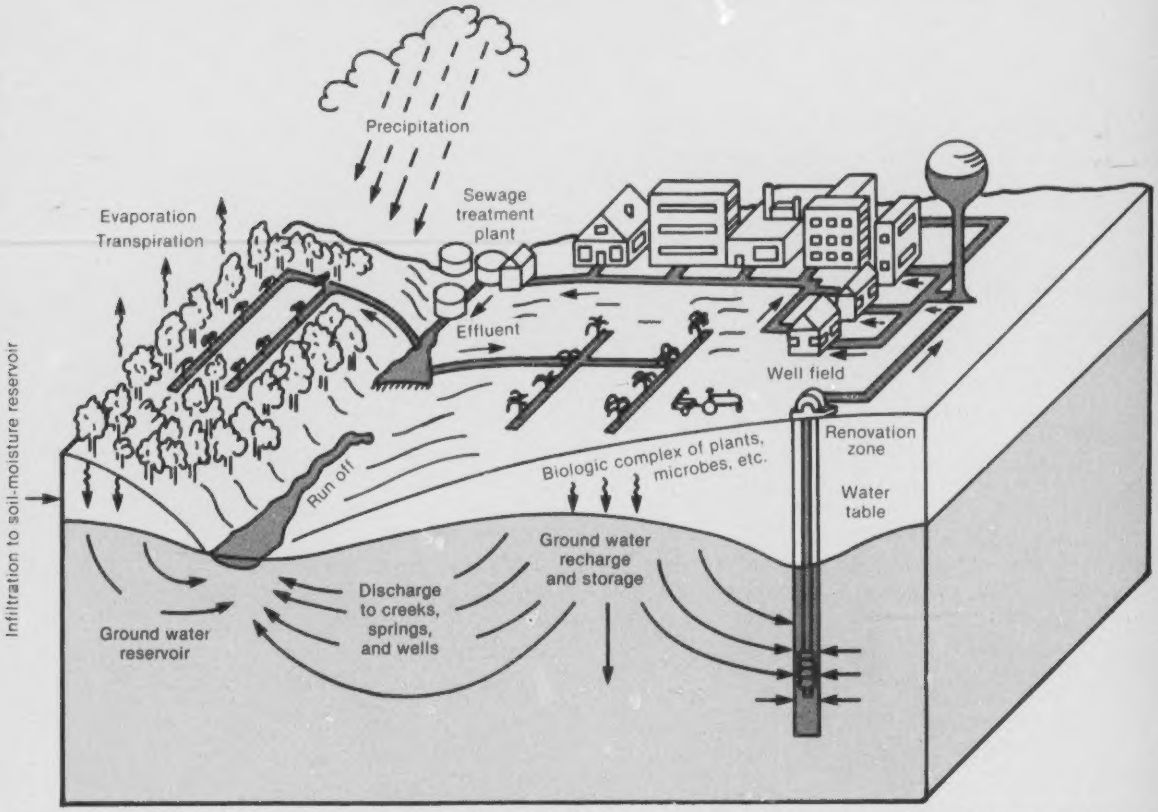
Wastewater reuse, defined as the use of land to renovate sewage effluent from municipal or industrial sources, is receiving increased attention as a possible way to augment irrigation water supplies and to reduce the water pollution that might otherwise occur if such wastewater were released directly to waterways. Those who advocate wastewater reuse consider that wastewater and the nutrients it contains are resources rather than refuse. Wastewater provides water and nutrients to plants. In return, biological and chemical processes that occur in the soil, micro-organisms, and plants are thought to cleanse the wastewater. According to supporters of this practice, renovated, safe water may then percolate downward to recharge the ground water reservoir or be discharged directly to surface water (fig. 71).

The idea of using land to treat wastewater is not new. Parker (22) notes that "treatment and disposal of sewage by land extensive schemes of irrigation is the oldest form of the modern methods of purification." These methods dominated U.S. municipal sewage-treatment systems until the early 20th century, but gradually diminished in importance as metropolitan areas expanded, large expanses of land adjacent to urban areas became limited, and concerns grew about possible public health and water-quality effects. Sewage treatments that used less land were developed as well.

Since the early 1970's, interest in land application technologies has revived. In part, this interest reflects a greater public awareness of the costs of treatment to meet health standards and of potential pollution and degradation caused by the discharge of partially treated wastes into waterways. It also reflects concerns about the growing scarcity of unallocated surface water supplies and rates of ground water depletion, especially in the West. Finally, Fed-

Figure 71.—The Wastewater Renovation Cycle

After treatment at a sewage-treatment facility, effluent is applied to the land. Biological and chemical processes that occur in the soil and plants provide further treatment for the wastewater. Renovated water then percolates to the ground water or is discharged directly to the surface water.


Precipitation
Evaporation
Transpiration
Sewage treatment plant
Effluent
Well field
Renovation zone
Water table
Biologic complex of plants, microbes, etc.
Run off
Infiltration to soil-moisture reservoir
Ground water recharge and storage
Discharge to creeks, springs, and wells
Ground water reservoir

SOURCE: William E. Sopper "Surface Application of Sewage Effluent," *Planning the Uses and Management of Land*, Marvin T. Beatty, et al. (eds.) (Madison, Wis.: American Society of Agronomy, 1979), pp. 633-663. (No. 21 in the series *Agronomy*.)

eral actions—e.g., passage of the Water Pollution Control Act of 1972 (Public Law 92-500)—have stimulated interest in reuse technologies to balance treatment costs.

Wastewater Treatment Methods

Wastewater contains two major categories of contaminants: biological and chemical. Biological contaminants include bacterial or viral pathogens and intestinal parasites. Chemical contaminants include substances such as nitrates, sodium, heavy metals (e.g., cadmium, lead, and zinc), oil, grease, and pesticides.

Levels of treatment generally recognized for wastewater are primary, secondary, and tertiary. This classification is based on the removal of suspended solids and on the reduction of biochemical oxygen demand (BOD)—i.e., the oxygen needed to meet metabolic needs of aerobic micro-organisms in water containing organic matter. Primary treatment consists of mechanical and physical removal of suspended solids. This process is estimated to remove approximately 35 percent of the BOD and 60 percent of the suspended solids in raw sewage water (26).

Secondary treatment introduces biological processes—e.g., activated sludge or trickling filters—to remove much of the remaining suspended solids and organic matter. Secondary treatment will remove from 80 to 95 percent of the BOD and suspended solids (26).

Tertiary, or advanced wastewater, treatment is used after primary and secondary treatments to reduce BOD further, remove suspended solids, lower nutrient concentrations, and improve the effectiveness and reliability of disinfection. Land application of wastewater is considered one method of tertiary treatment along with others such as chemical coagulation, clarification, filtration, activated carbon treatment, and reverse osmosis.

Advanced wastewater treatment by land application can be achieved in a variety of ways, depending on the goal of the treatment, the composition of wastewater, and characteristics of the waste site. The three most commonly used methods for land application are slow-rate irrigation, overland flow, and rapid infiltration-percolation. Table 76 compares the three methods by use objectives.

Slow-rate irrigation (fig. 72-A) is probably the method used most often and with most potential for agricultural use. In this process, wastewater is applied to the soil surface by a fixed or moving sprinkler system or by surface irrigation. Water application rates are generally low and are largely determined by climate, soil, and the water and nutrient needs of the crops. Treatment proceeds as vegetation and soil micro-organisms act to remove and alter wastewater as it percolates through the soil.

Overland flow reuse systems (fig. 72-B) also rely on a vegetative cover to effect waste treatment but differ from slow-rate methods because crop production is usually not a major objective. In this process, wastewater is applied over the upper parts of vegetated terraces and allowed to flow in a thin sheet down the relatively impermeable surface to runoff collection ditches. Only small amounts of wastewater infiltrate into the soil or percolate to the ground water. Renovated water that is collected may be reused or discharged directly to surface water. Treatment occurs by physical, chemical, and biological means.

Table 76.—Comparison of Irrigation, Overland Flow, and Infiltration-Percolation of Municipal Wastewater

	Type of approach		
Objective	Irrigation	Overland flow	Infiltration-percolation
Use as a treatment process with a recovery of renovated water[a]	0-70% recovery	50-80% recovery	Up to 97% recovery
Use for treatment beyond secondary:			
1. For BOD[b] and suspended solids removal	98 + %	92 + %	85-99%
2. For N removal	85 + %[c]	70-90%	0-50%
3. For P removal	80-99%	40-80%	60-95%
Use to grow crops for sale	Excellent	Fair	Poor
Use as direct recycle to the land	Complete	Partial	Complete
Use to recharge ground water	0-70%	0-10%	Up to 97%
Use in cold climates	Fair[d]	—[d]	Excellent

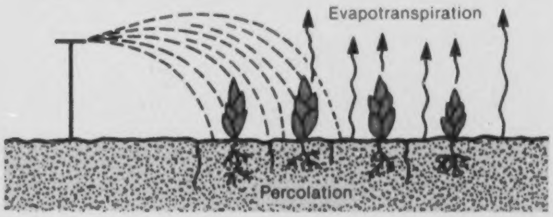
[a] Percentage of applied water recovered depends on recovery technique and the climate.
[b] BOD = Biochemical oxygen demand.
[c] Dependent on crop uptake.
[d] Conflicting data—woods irrigation acceptable, cropland irrigation marginal.
[e] Insufficient data.

SOURCE: William E. Sopper, "Surface Application of Sewage Effluent," *Planning the Uses and Management of Land*, Marvin T. Beatty, et al. (eds.) (Madison, Wis.: American Society of Agronomy, 1977), pp. 633-663. (No. 21 in the series *Agronomy*). (Original source: U.S. Environmental Protection Agency, "Process Design Manual for Land Treatment of Municipal Wastewater," EPA 625/1-77-008 (Washington, D.C., 1977).

Figure 72.—The Major Types of Wastewater Treatment

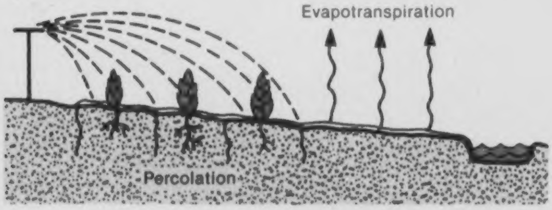
A. Slow-rate irrigation

Wastewater is applied to the soil surface and allowed to percolate downward. Treatment proceeds as soil, vegetation, and soil micro-organisms remove nutrients and suspended solid material.



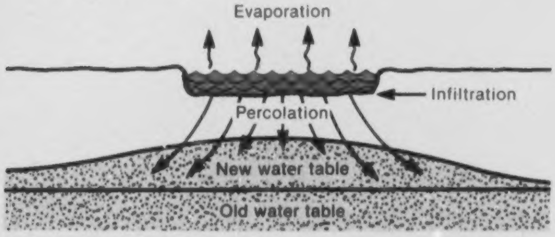
B. Overland flow reuse

Wastewater is applied to a sloping surface and allowed to flow over the soil surface to runoff collection ditches. Treatment is a result of physical, chemical, and biological processes.



C. Rapid-infiltration percolation

Wastewater is applied by flooding or sprinkling to highly permeable soils in basins. As the wastewater percolates into the soil, renovation occurs.



SOURCE: William E. Sopper "Surface Application of Sewage Effluent," *Planning the Uses and Management of Land*, Marvin T. Beatty, et al. (eds.) (Madison, Wis.: American Society of Agronomy, 1979), pp. 633-663. (No. 21 in the series *Agronomy*.)

Rapid infiltration-percolation, the third method, uses less land area to effect treatment than do the other two methods. The main objective in this system is ground water recharge (fig. 72-C). Wastewater is applied to highly permeable soils in basins by flooding or sprinkling. The basins may or may not be vegetated. Renovation occurs through natural processes in the soil as water percolates downward.

The degree of success for wastewater treatment varies with the type of method used to apply wastes. Table 77 shows expected treatment performance for these three processes.

ASSESSMENT

Municipal wastewater is now used for irrigation. However, information on the number of communities that use land treatment for sewage renovation and the number of individuals who use wastewater to irrigate agricultural crops is inexact, because funding for these systems may be through the Federal Government, industry, or private sources. With Federal funding, estimates are that approximately 1,000 municipalities use land application to treat wastes (31). Unpublished data from the U.S. Geological Survey (USGS) indicate that in 1980, 0.5 billion gal/day of effluent were used for irrigation compared to 290 billion gal/day of fresh surface water and 88 billion gal/day of fresh ground water.

Some communities use municipal wastewater for irrigation for parks, golf courses, and greenbelts and Federal and State guidelines have been developed for its application (e.g., 22,36). In California, for example, irrigation return flows of relatively good quality are applied to wetland areas to maintain natural vegetation. These areas are then used for cattle grazing in summer and hunting in the fall. Chemical wastes from potato processing plants have also been used for irrigation. In spite of these signs of acceptance, widespread adoption of reuse systems for most agricultural crops is hindered by numerous biological, social, economic, and legal questions and a lack of long-term research on the subject. Chapter IV discusses some of the more serious public health questions that still need answers before full-scale programs should be adopted. Table 78 presents a summary of issue areas that require resolution.

Three examples illustrate the complexity of these issues. First, regarding the question of

Table 77.—Expected Quality of Treated Water From Land Treatment (mg/liter)

	Slow rate[a]		Rapid infiltration[b]		Overland flow[c]	
Constituent	Average	Maximum	Average	Maximum	Average	Maximum
BOD	<2	<5	2	<5	10	<15
Suspended solids	<1	<5	2	<5	10	<20
Ammonia nitrogen as N	<0.5	<2	0.5	<2	0.8	<2
Total nitrogen as N	3	<8	10	<20	3	<5
Total phosphorus as P	<0.1	<0.3	1	<5	4	<6

[a] Percolation of primary or secondary effluent through 1.5 m (5 ft) of soil.
[b] Percolation of primary or secondary effluent through 4.5 m (15 ft) of soil.
[c] Runoff of municipal wastewater over about 45 m (150 ft) of slope.

SOURCE: William E. Sopper, "Surface Application of Sewage Effluent," *Planning the Uses and Management of Land*, Marvin T. Beatty, et al. (eds.) (Madison Wis.: American Society of Agronomy, 1977), pp. 633-663. (No. 21 in the series of *Agronomy*). (Original source: U.S. Environmental Protection Agency. "Process Design Manual for Land Treatment of Municipal Wastewater," EPA 625/1-77-008 (Washington, D.C., 1977.)

land productivity with reclaimed water, data indicate that the yields of crops irrigated with wastewater usually increase or remain the same (9,26), but crops seem to vary in their tolerance to wastewater application (table 79). For example, research in Hawaii on sugarcane tested the dilution of wastewater required for optimal sugar yield (18). Five treatments for the 2-year cane cycle were tested: 1) conventional irrigation water, 2) 12.5-percent effluent diluted with irrigation water, 3) 25-percent sewage water, 4) 50-percent effluent diluted with ditch water, and 5) effluent the first year and irrigation water the second year. Scientists found that sugar yields for wastewater concentrations up to 25 percent, or for wastewater the first year and irrigation water the second year, were equal to those from conventional irrigation supplies. When wastewater concentrations increased to 50 percent, however, sugar yields and juice quality declined significantly. The researchers concluded that chlorinated, secondarily treated sewage effluent with nitrogen concentrations could be used in furrow irrigation for the 2-year crop cycle of sugarcane if wastewater were diluted with freshwater so that the concentration of effluent was 25 percent or less. They cautioned, however, that effluent quality must be constantly monitored for nitrogen content, pesticides, heavy metals, and pathogenic viruses. Such substances in the soils or waterbodies could prove difficult, if not impossible, to eliminate (chs. IV and X). In addition, field workers were warned to practice careful sanitation and personal hygiene to protect against infection.

A second illustration provides a sample of the economic questions that surround application of wastewater for irrigation. Although effluent was generally recognized as a valuable resource for water and nutrients, few farmers actually measured the fertilizer value of the water. Similarly, those in local governments responsible for the operation of reuse systems acknowledged the economic value of the effluent but had not established procedures to charge landowners or farm operators for the value that they received. Instead, they took the view that landowners performed a service in disposal of municipal waste effluent.

Third, with regard to social concerns, public reaction may be an obstacle to wastewater reuse. A survey of selected California communities indicated that respondents favored water treatment options that protected public health, enhanced the environment, and conserved scarce water (5). However, use of reclaimed water for ground water recharge and drinking supplies was perceived as a threat to human health. Effluent used for industrial purposes or for irrigation of animal feed and fiber crops was considered to be an acceptable practice (6). The inconsistency arises when contaminants from effluent reach the ground water secondarily, as the result of its use in industry or irrigation.

Wastewater reuse has been adopted by relatively few communities and farmers in the United States. It can potentially supplement irrigation water supplies and reduce reliance on added fertilizer, but generates many questions

Table 78.—Summary: Issues Surrounding Water Reuse for Irrigation

Resource issues:

1. Effluent quality:
    - —Nutrient content
    - —Heavy metal content
    - —Pathogen content
2. Soil productivity:
    - —Salt buildup
    - —Toxicity buildup
    - —Viral contamination
    - —Physical degradation
3. Crop production:
    - —Fertilizer and water requirements
    - —Crop growth and yields
    - —Crop uptake of nutrients
    - —Crop uptake of toxics and pathogens
4. Animal health:
    - —Animal uptake of nutrients
    - —Animal transmission of pathogens to human consumers
5. Ground water quality:
    - —Path of water to water table
    - —Quality of water reaching ground water
6. Air quality (with sprinkler irrigation)
    - —Health effects for workers and nearby residents
    - —Odor considerations

Social and economic issues:

1. Human health effects:
    - —Contact with effluent by farmworkers
    - —Contact with plant and animal products by consumers
2. Social factors
    - —Public attitudes toward application
    - —Public attitudes by consumers of products
    - —Attitudes of nearby residents
3. Economic considerations:
    - —Water pricing
    - —Transportation costs
    - —Subsidies for those who use water
    - —Facilities for water storage
    - —Value in alternate uses
    - —Type of material contained in water

Institutional issues:

1. Water-treatment facilities
    - —Adequacy and reliability of treatment prior to application
    - —Adequacy of storage facilities during periods of nonapplication
2. Monitoring
    - —Need for monitoring air, effluent, ground water, crop, and soil quality
3. Legal issues
    - —Ownership and sale of water
    - —Water rights
    - —Liability for damages
    - —Responsibility for monitoring
    - —Guidelines for water reuse (e.g., crops to be grown, amount of water to be applied)
    - —Effect on downstream users (third parties), if water previously was part of return flows

SOURCE: William H. Bruvold, *Agricultural Use of Reclaimed Water*, unpublished paper prepared for National Science Foundation, January 1982. Office of Technology Assessment, 1982.

Table 79.—Crop Yields at Various Levels of Application of Wastewater, Pennsylvania State University

	Wastewater Application Rates, inches per week[a]		
Crop	0[b]	1.0	2.0
		(bushels/acre)	
Wheat	48	45	54
Corn	73	103	105
Oats	82	113	88
		(tons/acre)	
Alfalfa	2.2	3.7	5.1
Red clover	2.4	4.9	4.6
Corn stover	3.6	7.3	8.5
Corn silage	4.3	6.4	6.0
Reed canarygrass	1.4	—	5.0

[a] Metric units in original document have been converted to English units.
[b] Control areas received commercial fertilizer ranging from 10 tons/acre of 0-20-20 for oats to 40 tons/acre of 10-10-10 for corn.

SOURCE: William E. Sopper, "Surface Application of Sewage Effluent," *Planning the Uses and Management of Land*, Marvin T. Beatty, et al. (eds.) (Madison, Wis.: American Society of Agronomy, 1977), pp. 633-663 (No. 21 in the series *Agronomy*). (Original source: U.S. Environmental Protection Agency, "Process Design Manual for Land Treatment of Municipal Wastewater," EPA 625/1-77-008 (Washington, D.C., 1977).)

on long-term impacts for soil and water quality and, ultimately, public health. Wider application of reuse systems will require careful planning and monitoring by municipalities and irrigators. The costs and danger of handling wastewater will have to be balanced with economic benefits of its reuse. In addition, when applied on a massive scale, questions are raised about the impacts of this water shift on other aspects of the hydrologic cycle, especially streamflow, if the treated water has previously been part of return flows. Moreover, legal considerations for downstream users may be complex. Much research has been done on this topic, but additional long-term research on the effects of these systems on crops, soils, ground water, and human and animal consumers is needed.

Water Management by Conjunctive Use

INTRODUCTION

The concept of conjunctive use is predicated on shifts between surface and ground water use and storage. During periods of above-average precipitation, or seasons of above-average runoff, surface water would be used to the maximum extent possible to fulfill various water requirements. Any surplus water would be used to recharge ground water supplies and raise ground-water levels. During dry periods, surface water supplies would be supplemented by ground water reserves.

ASSESSMENT

Whether conjunctive management of a basin's water is technically practical depends on local geology and the extent to which ground water resources are manageable over a range of water levels. There must be space to store recharge water, there must be water in storage when and where it is needed, and there must be the physical facilities and energy available to transport surface and ground water.

Management by conjunctive use requires careful planning to optimize the use of the available surface and ground water resources. Detailed, site-specific engineering and economic analyses are needed to determine optimal mixes of surface and ground water storage.

A conjunctive use management approach requires more information than is commonly necessary for the use of either surface or ground water resources separately. In the most general terms, these information requirements include detailed data on surface and ground water resources, the geologic conditions of the basin, interconnections of surface and ground water supplies, water-distribution systems, historical and projected water-use patterns, and wastewater disposal practices.

Commonly, except perhaps in the simplest situation, mathematical models are required to describe the reaction of the ground water reserves to fluctuations in natural and artificial recharge and to varying pumping rates. Such models are available, but they vary widely in capability and limitations and must be used carefully. State governments indicate the desire for more resource models, while the Federal Government needs to better coordinate the use of models among various agencies (32).

Ultimately, decisions concerning the feasibility of conjunctive use management of water resources must also include an assessment of the relative economic benefits of constructing additional surface storage facilities, the increased complexity of conjunctive management approaches, and the cost of energy to pump water from aquifers. Because each project will be unique, no universal rules exist governing the economics of this approach to water management. Some of the advantages and disadvantages are listed in table 80.

Enclosures for Plants and Fish

INTRODUCTION

Greenhouses are commonly used in the United States to grow horticultural products such as flowers and houseplants. In Europe, enclosures are used also for crops primarily of very high economic value, such as table vegetables. In the Middle East and Asia raising fish in enclosures is an ancient applied science. Aquaculture in various forms provides over 40 percent of total fisheries production in some countries but only about 2 percent of total fisheries products (7).

Many features of arid and semiarid lands make them especially suitable for growing plants or fish in enclosures: solar energy is abundant, growing seasons are long, and winters are often mild. Typically, the efficiency with which water is used is very high, and intensive management allows for the most efficient use of other substances such as fertilizers and pesticides.

Plant and fish enclosures vary widely in scale. Some are major corporate enterprises requiring large investments to initiate. Others are suitable for production of a few items for household use and local sales.

ASSESSMENT

Experiments around the world with highly sophisticated systems show that crop yield in controlled environments is several times that of field-grown crops. For example, enclosures in Mexico and Abu Dhabi yielded almost 20 different fruits and vegetables at production levels often several times higher than field-grown equivalents with about one-third the use of water and significantly shorter growing seasons.

Table 80.—Conjuctive Use of Surface Water and Ground Water Resources

Advantages	Disadvantages
1. Greater water conservation	1. Less hydroelectric power
2. Smaller surface storage	2. Greater power consumption
3. Smaller surface distribution system	3. Deceased pumping efficiency
4. Smaller drainage system	4. Greater water salinity
5. Reduced canal lining	5. More complex project operation
6. Greater flood control	6. More difficult cost allocation
7. Ready integration with existing development	7. Artificial recharge is required
8. Facilitated stage development	8. Danger of land subsidence
9. Smaller evapotranspiration losses	
10. Greater control over outflow	
11. Improvement of power load and pumping plant use factors	
12. Less danger from dam failure	
13. Reduction in weed seed distribution	
14. Better timing of water distribution	

SOURCE: D. K. Todd, *Groundwater Hydrology*, 2d ed. (New York: John Wiley & Sons, 1980). (Original source: F. B. Clendenen, "Economic Utilization of Ground Water and Surface Water Storage Reservoirs," presentation to American Society of Civil Engineers, San Diego, Calif., February 1955.)

Photo credit: Food and Agriculture Organization—U. Pizzi

Many types of plant enclosures exist. These plastic tunnels in Malta, protect horticultural crops, such as grapes, vegetables, and flowers

These results are possible because the systems are completely or nearly closed, humidity remains high, and irrigation water is recycled. Enclosures also insulate the grower from the unpredictable climate of arid and semiarid regions and help stabilize production. Marketing is also independent of weather, and it can be timed to take advantage of highest prices.

Scientists and engineers continue to refine technical aspects of these structures. In the face of rising energy costs, systems that use solar energy appear promising for long-term production. Bettaque (3) described "eco-islands in the desert" that use solar energy and saltwater to heat and cool greenhouses while distilling freshwater. He found that such enclosures use minimal amounts of fossil fuel energy, have capital costs comparable to conventional green houses, and that increased crop yields are possible with little technical sophistication. Similar Israeli systems use a closed cycle of freshwater to absorb solar radiation. Practices that may not be technically possible in open fields, such as atmospheric enrichment with higher levels of carbon dioxide, are also being attempted in enclosures (24).

Plant enclosures will not produce large amounts of inexpensive food because the capital costs for large installations are usually high and operating such enclosures may be labor- and energy-intensive. While basic agronomic crops grow well in enclosures, they are not expected to be grown commercially in this way in the foreseeable future. The development and use of less common types of plant enclosures face many of the same constraints listed below for aquaculture. For example, most agricultural experts are not familiar with integrated plant/fish enclosures or greenhouses, such as attached solar enclosures of unusual design.

Some aquaculture (or a combination of aquaculture and plant production systems) may be possible in U.S. arid and semiarid zones. Preliminary tests suggest that aquaculture in the West is feasible (27). For instance, recent research in Nevada has shown that shrimp can be grown in ponds heated by geothermal springs or by warm wastewater from electric generating plants (30). Several Western States have extensive hatchery and release programs that could be further developed. Generally, the potential for aquaculture is rated highly. There is an extensive market for seafood in the United States and more than 50 percent is imported (7). Few aquaculture attempts have been undertaken commercially in the Western United States, however, and the further development of integrated plant/fish and fish systems faces severe constraints. For example, water requirements for fish culture could be substantial and require diversions from other uses. Other problems include:

- inadequate funding for research and development;
- poor marketing practices;
- inexpensive imported products;
- regulatory controls, especially standards for waste discharges;

Photo credit: USDA-Soil Conservation Service

The potential for aquaculture in the Western United States is high. In Texas, these channel catfish have been seined from a pond and separated from other fish. From here, they will be transported to a feeding pond

- uncertain availability of high-quality water;
- lack of trained personnel; and
- overcoming a bad image from past failures.

For these and other reasons, aquaculture is not expanding rapidly in the United States. Government, industry, and academic experts have recommended that the United States develop a national aquaculture development plan and improve coordination of present Federal programs in order to increase aquaculture's contribution to fisheries production.

Land Use Management

Most farms and ranches produce one product and use highly energy-intensive practices such as chemical fertilization and pesticides. With uncertain economic and resource conditions, such as increasing energy costs and unknown water availability, such specialization may involve greater risks. Therefore, technologies that integrate different types of land use and different types of agricultural and nonagricultural products hold promise for stabilizing economic risk and are perceived by some as the direction of the future.

The technologies discussed in this section are diverse and reflect a spectrum of agricultural philosophies. For example, multiple land use on rangelands falls within accepted traditional practice, but the various types of alternative agriculture are, by definition, not traditional technologies.

Multiple Use of Rangeland

INTRODUCTION

Rangelands in arid and semiarid lands are being used increasingly by different kinds of people for very different purposes. This is an important feature of publicly owned rangelands and is required by law for Federal lands. This concept is also being developed for some privately owned lands. Under these conditions, the highest animal, plant, or water production per unit area is not necessarily maximized. For example, plants that are "unproductive" in agricultural terms may be allowed to remain along streambanks for the other important amenities that they provide. When the efficiency of water use is measured in terms of all products per unit of water used, such multiple uses may be more water-use efficient than would traditional single uses such as grazing.

Major present multiple uses of rangeland include livestock and wildlife grazing, recreation, and mining. Uses that are less important include harvesting nonforage plant products, such as seeds and nuts, providing military reservations and waste disposal sites, producing nonmeat animal products, and producing water for offsite use.

All of these activities have hydrologic effects, some greater than others. However, the relative importance of each potential use and its impacts on water resources shift from area to area and continue to change. In some States, public rangelands provide a great deal of water-based recreation; in others, mining activity is concentrated on these sites.

ASSESSMENT

Range managers often operate without an adequate data base, making multiple-use management especially difficult. Because Western grasslands were altered by human settlement before data were collected, major gaps in the understanding of the structure and function of these areas exist. Early managers did not place high emphasis on data collection. Even now, the long-term effects of specific management practices are unknown. For example, the results of stocking rates recommended by the Bureau of Land Management for individual users are not systematically monitored.

Intensive management of any resource is made especially difficult under such circumstances. The tendency is to "maximize" all uses, leading to the nonsustainable use of the resource. Considerable debate has ensued recently over the results of applying the multiple-use concept to public rangelands. Some contend that it will diminish the value of public rangelands for grazing livestock. Others contend that multiple use discourages ranchers

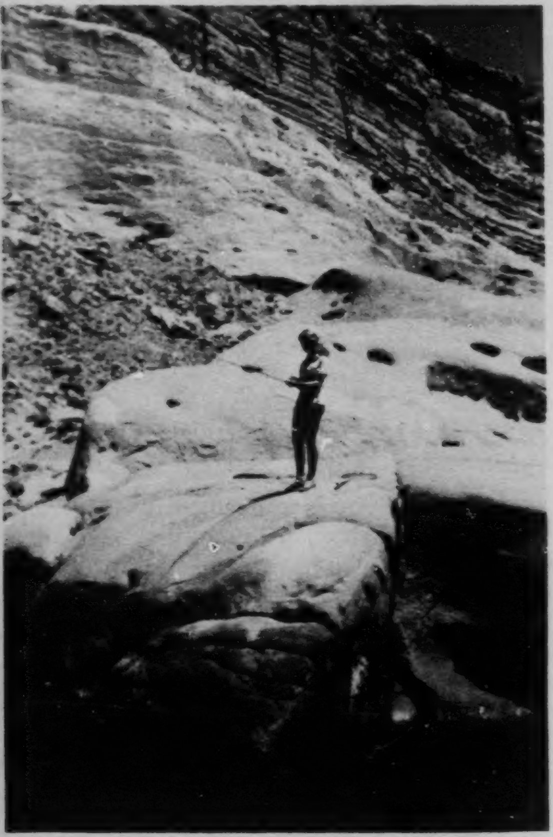


Photo credit: U.S. Department of the Interior, National Park Service

Federal lands provide a great deal of water-based recreation, including fishing, swimming, and boating

from overgrazing and will, in the long term, improve range conditions.

Many factors outside of the agricultural sector determine the future importance of multiple uses of all land types. The growing Western urban population has led to the increase in recreational use of rangelands. The search for new energy sources has stimulated mining activities. Some of these activities are discussed below.

Factors Determining Future Multiple Use of Rangelands

Wildlife.—Arid and semiarid rangelands provide habitats for a significant number of wildlife species, including mammals, birds, and fish. These animals attract large numbers of visitors to the region and are of great interest to residents as well. Wildlife considerations strongly influence water management on many rangelands, and intensive water management has important effects on wildlife. Technologies for wildlife management usually do not require additional supplies of impounded water but may result in increased rangeland productivity per amount of water used (21,27).

Wildlife species normally require freshwater of reasonably good quality. Water consumption rates are virtually unknown for most wildlife species, but they are not thought to be great. For example, total water consumption by big game animals may range from 100,000 to 130,000 acre-ft/year for the entire Western range (27). Water distribution and quality are more critical factors. Bighorn sheep are adapted for high water conservation, but their distribution depends on available drinking-water supplies. Mule deer populations show major changes if the nearest water supply is farther than 3 miles (38).

Inland rangeland fisheries depend on the maintenance of lakes, perennial streams, ranch ponds, and reservoirs. These features also provide habitat for waterfowl, an especially important rangeland resource in the northern Great Plains. Water levels must be consistently maintained for fish and waterfowl to survive. Sometimes this is not economically feasible and usually it is not legally required.

Irrigation in the same watershed may lower water tables and reduce both streamflow and riparian and upland wildlife habitat. Other agricultural practices, such as the use of chemical or mechanical methods to eliminate unwanted plants, alter the cover and food supply on which wildlife depend. After considering the major effects that agricultural practices can have on wildlife, the National Research Council (21) recommended that there be three requirements for optimizing all resources, including water and agricultural production. These are:

- promotion of attitudes encouraging stewardship of wildlife;
- additional critical research on conservation tillage, irrigation patterns, pesticide

effects, and nutrients in aquatic systems; and

- consistent public policies that use incentives to enhance fish and wildlife habitats.

Recreation.—Recreational use of rangelands has increased dramatically in recent years. Much of this activity is water-based, either directly—e.g., fishing—or indirectly—e.g., hunting. Some recreational activities make extensive use of shorelines of existing water bodies. Range managers sometimes develop new sources of water from natural seeps, low-yield springs, and wells for these uses. These developments supplement and expand water supplies on rangelands. However, goals for livestock production and recreational opportunities sometimes are incompatible and management is difficult. In Texas, for example, where deer and other wildlife are hunted through leases, ranch managers often give more attention to providing accommodations to hunters than to actual management of the deer herds (8).

The income from hunting leases to a rancher with private lands can be substantial. In Texas, where there are few public lands available for hunting and most private lands are protected from trespassing, hundreds of thousands of acres are leased for hunting each year at prices of up to $10 per acre (8). Income from leasing in many cases exceeds that from the sale of livestock, the primary use of the land. Hunters paid landowners $108 million for leases in 1971 (2), and the average cost of each lease has increased two to three times since then (21).

Applegate (1) asserts that Texas is representative of other States and that there are examples of ranchers in every State who lease hunting land. In Oregon, where public land is available for hunting, leasing arrangements on private ranches are increasing. In many areas of the West, though, the lands used for recreation are public lands. Income from hunting permits and tourism accrue to the States and local businesses, not to ranchers.

Nonforage Plant Products.—Uses and income derived from nonforage plant products are not well documented, but they are significant for certain users in certain areas. For example, seeds are harvested in some areas for range reseeding, mineland reclamation, and urban horticultural use (fig. 73). Some seeds may bring prices as high as $8/lb (12).

Pinyon pine nuts have been a staple food source for American Indians throughout the intermountain States. The few nuts reaching urban markets are prized. Potential exists for maximizing production of native stands and also harvesting nuts from areas unsuitable for any other crop. Some range plants have potential as biomass fuel sources (see ch. IX for a detailed discussion). Other potential plant products include wooden jewelry and fibers for basketry and paper. These activities will probably continue and may increase in the face of declining water supplies for other uses.

Nonmeat Animal Products.—The production of many nonmeat animal products, such as fur, wool, and hides, can increase substantially without seriously affecting water resources. Since most produced now are not sold, their sale would represent an increase in agronomic water-use efficiency. See the discussion on animal mixtures, below.

MULTIPLE-USE TECHNOLOGIES

The multiple-use concept has been instrumental in shaping technology development and adoption for rangelands. Two examples follow, one in which technology developed for the mining industry is moving into agriculture and one in which agricultural technology was refined by multiple-use demands.

Surface-Mined Land Reclamation

Introduction.—Mining activity is widespread on Western rangelands and on some crop and pasturelands. Coalfields in Montana, Wyoming, North Dakota, South Dakota, Utah, Colorado, New Mexico, and Arizona underlie more than 100 million acres. Approximately 90 additional minerals are found in sufficiently large deposits to be mined.

Mining activities influence water in many ways. Water that flows through a mining area may be degraded in water quality, a conse-

Figure 73.—Summary Information for Using Big Sagebrush in Rangeland Reclamation

Big Sagebrush (*Artemisia tridentata*)

Characteristics

Height:	1.5 to 9 ft (0.5 to 3 m)
Spread:	1 to 5 ft (0.3 to 1.5 m)
Growth form:	Round, generally erect, multi-branched, evergreen shrub
Root-system type:	Deep, spreading

Habitat

Distribution:	Nebraska to eastern California, south to New Mexico, Arizona
Elevation:	1,500 to 10,600 ft (495-3,500 m)
Topography:	Wide spread, low-elevation rangeland to mountain slopes
Salt tolerance:	Fair
Drought tolerance:	Good
Soil:	Fine- to coarse-textured, acidic and basic, moderate to deep, well drained

Use

Forage value:	Important for wildlife on winter rangeland
Erosion control:	Control mass-soil slippage
Landscaping:	Gray-green foliage

Propagation

Seed:	Good germination at room temperature but is speeded at cooler temperatures: seeds ripen late September
Vegetative:	Collect stem cuttings Feb. to April treat with 2.0% IBA powder

SOURCE: Institute for Land Rehabilitation, "Selection, Propagation, and Field Establishment of Native Plant Species on Disturbed Arid Lands," Utah Agricultural Experiment Station Bulletin 500, 1979.

quence of the mining process (ch. IV). Substantial water supplies may be required during mining operations and stream widening. Lake drainage, surface-flow diversions, streambank disruption, and ground water interference may all occur. Collectively, mining activities affect water supplies and the use of the land for agriculture.

Mining also has indirect effects on water use. Surface mining destroys existing natural communities completely and dramatically. Because water is the major factor in revegetating these areas, many reclamation efforts focus on water use and management.

Assessment.—Most arid and semiarid rangelands have not and will not face such drastic disturbances. Probably only a small percentage of all rangelands will be surface mined for coal. Yet water remains the key to maintaining or restoring rangeland productivity. As a result of these similarities, many reclamation technologies can be used directly on other rangelands. This is important because Congress has mandated improving the condition of the 160 million acres of public rangelands in the 17 Western States and recent legislation* established a national commitment to maintain and improve public and private rangelands, making them as productive as feasible for all rangeland values. Until now, such improvements were slow and few technologies existed.

Reclamation technologies are not expected to increase agronomic water-use efficiency of plants or animals greatly, but preliminary research suggests that some gains can be made (27). A variety of technologies are possible:

- water-retention methods to speed plant establishment and minimize runoff,
- plant breeding for hardy and palatable grasses,
- planting and seeding technology,
- soil building techniques, and

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*Forest and Rangeland Renewable Resources Planning Act, (Public Law 93-378); Public Rangelands Improvement Act, (Public Law 95-514).

- management of vegetation composition and ecosystem analysis.

Dryland sodding is an example of a technology to prevent erosion and to establish plant cover rapidly. With this technique, thickly cut native sods containing grasses, forbs, and shrubs are placed on steep, erosive slopes and special machines have been developed to handle native sod efficiently and effectively.

In the past, rangeland managers avoided the use of many potentially useful plant species on undisturbed lands owing to problems with seed size and shape, low germination, or seedling vigor. Because regulations require large proportions of native plants in reclaimed areas, new planting and seeding technology was stimulated. Special techniques and equipment now exist for harvesting, treating, and planting fuzzy, awned, sticky, minute, or otherwise troublesome seeds. In some cases, the vulnerable seed and seedling stages are protected by specially designed containers or underground stem and root transplants are used in revegetation efforts on marginal or "impossible" sites.

The productivity of some undisturbed range sites is limited by soil conditions—e.g., high sodium or clay content—that affect nutrient and water availability as well as toxicity to plants. Surface mining requires the complete reconstruction of soils. Therefore, reclamation research has stimulated the development of soil building technologies that have the potential for transfer to other lands. These include the use of biological, chemical (organic and inorganic), and physical amendments to the soil.

Most surface mining regulations have rigid requirements for determining the success of reclamation. In some cases, the composition of vegetation is specified. As a result, interest has increased in vegetation management methods as well as in long-term ecosystem analysis. Some management methods, such as rangeland fertilization, burning, irrigation, interseeding, and grazing, were developed for undisturbed rangelands but are being refined by reclamation efforts. Others, such as long-term analyses of plant/environment interactions, are seldom matched in duration or intensity by traditional rangeland research (25).

Legal, social, political, economic, and cultural factors may be barriers to implementation of reclamation technologies on undisturbed rangelands. For example, Federal law on the use of native plants and land with agricultural potential has affected State regulation and research. Schechter (24) maintains that R&D are inadequate and that capital does not exist to meet this need. A single discipline focus hinders application of the research that has been done. For example, undisturbed rangelands may contain more than 40 plant species, but revegetation efforts often focus on a single species. Moreover, there is a general lack of understanding of soil biota. More information about complex multiple species interactions is needed, a task requiring an interdisciplinary effort.

Economic return varies widely among Western agricultural land uses, making certain technologies suitable for some lands but not for others. For example, private companies may spend $2,500 to $6,000/acre to reclaim land that has been surface mined for coal (14). A nearby acre of undisturbed land may sell for $200. Clearly, reclamation is costly, even when disturbance is less drastic than that from surface mining. Improvement of unmined but degraded public rangelands using a variety of technologies would represent a major economic investment. The Bureau of Land Management has a backlog of $34.7 million in needed range improvements, and the cost of additional projects is estimated to be over $148 million (37).

Management of Undesirable Plants and Animals

Introduction.—Range managers identify a number of plants that decrease livestock forage or have other undesirable features. Some of these plants are not natives of the West but have spread after introduction from other parts of the world. Undesirable plants may be highly adapted to arid and semiarid conditions and therefore difficult to remove once established.

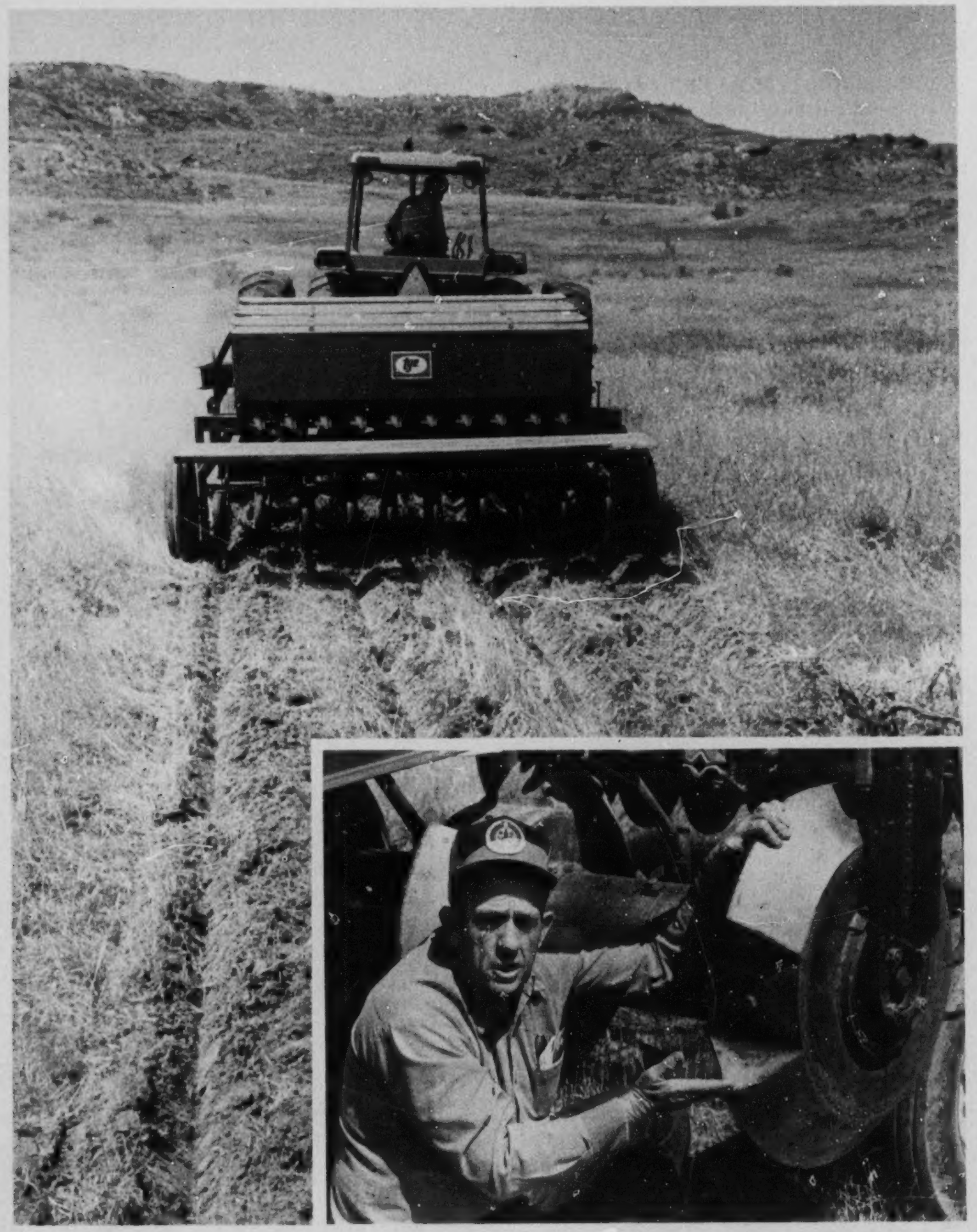

Photo credit: USDA-Agricultural Research Service

The Range Improvement Machine is being developed by USDA/ARS in cooperation with Montana State University for use on semiarid rangelands and marginal pasturelands to increase grass and forage yields. It uses a packing wheel system. For purposes of water conservation, the gap in each wheel leaves a check dam at 7-ft intervals (inset)

The definition of plant pests depends on the intended land use and the specific site, but plants such as mesquite, oaks, and sagebrush are often considered to be undesirable by ranchers.

Human use of rangelands has exacerbated the increase of plants considered undesirable. Intensive grazing, the exclusion of fire, and temporary cultivation have changed the composition of plant communities. Invasion of woody species also decreases the availability of forage for livestock and is the primary cause of rangeland degradation. Therefore, technologies to control "brush" are one way to increase rangeland productivity. Usually, large amounts of water are not directly involved in these technologies. Instead, increases in productivity lead to higher water-use efficiencies. Other applications of these technologies may be made to increase water runoff specifically (ch. VI).

In some parts of the West, principally in public rangelands in Utah and Nevada, wild horse and burro populations also degrade lands. Experts estimate that 60,000 to 70,000 wild horses compact soils, overgraze plants, and generally interfere with careful rangeland management and optimal use of forage. Programs to control these and other animals are used to achieve three management objectives: 1) protect livestock, 2) reduce the number of herbivores that compete with livestock for available forage, and 3) protect the range from overgrazing and subsequent damage to productivity. Most control programs seek to optimize population size, not to eliminate all wild animals.

Assessment.—Studies of several plant species indicate that control or removal significantly increases soil water, resulting sometimes in a concomitant increase in available forage for livestock. However, not all stands of undesirable plants use large amounts of water that would be available to other users, and the amount of water affected depends on the original type of vegetation, its density, local precipitation, and the control method used. In some cases, vegetation considered by ranchers

Box Z.—Integrated Brush Management: A New Approach for Degraded Rangelands

In the last few years, emphasis in range management has shifted from eradication of noxious plants to their careful control by combinations of methods, known as integrated brush management. The basic principles include:

- reducing dependence on any single control method,
- using the synergistic effects from treatment combinations,
- increasing both livestock and wildlife habitat,
- developing flexible treatments for different conditions,
- integrating treatments with other management techniques, and
- enhancing economic returns from brush management.

These techniques are applicable to most sites, but to be successful they require long planning horizons: brush-management systems are designed to span 15 or 20 years. These program are expected to be adopted first in areas that have major brush problems. For the next decade, Texas, Oklahoma, and New Mexico will probably be most involved. Adoption could increase rapidly if costs of other range-management technologies or Federal constraints on herbicide use increase.

The costs of these techniques vary widely, and there are additional indirect costs and benefits. Primary constraints to implementation are economic, especially for the first costly step in a sequence. Technical constraints are significant since research still is in the formative stage and treatment testing requires long time periods.

SOURCE: U.S. Congress, Office of Technology Assessment, *Impacts of Technology on U.S. Cropland Rangeland Productivity* (Washington, D.C.: U.S. Government Printing Office, OTA-F-166, August 1982).

to be undesirable provides important benefits. For example, most stands of trees and shrubs furnish wildlife habitat. They may also provide shade for livestock, protect soil from wind or water erosion, increase water runoff for offsite uses, or contribute to the attractiveness and diversity of arid and semiarid lands.

Each of the common brush-control technologies has advantages and disadvantages. Mechanical control is labor- and energy-intensive and thus expensive. After chopping and clearing plants, some residue usually remains, which is advantageous, but considerable soil disturbance also occurs. Chemical control is specific, effective, and often less expensive, but some chemicals, improperly applied, may cause crop damage or health hazards. Regulations largely prohibit chemical use on Western Federal rangelands. In contrast, fire, always a feature of Western rangelands, is gaining acceptance as a major control technology. It is inexpensive, but all areas cannot support fires and the resultant denuded ground is subject to soil erosion.

These conventional control technologies have been criticized for being used without regard to their effects on values other than livestock production. Integrated brush management is a newer technology that has the potential for enhancing multiple-use values of rangelands. Some experts contend that this technology can make a large contribution to increased water availability for agriculture on rangelands.

With an integrated approach, it is possible to manage noxious plants for their potential

Photo credit: USDA-Soil Conservation Service

Fire is gaining acceptance as an effective brush-control technique. Here, junipers are ignited to increase forage production on rangeland in Arizona benefits. For example, because mesquite may form very dense stands, and cattle sometimes have difficulty digesting mesquite pods, mesquite is often considered to be noxious. But these trees have traditionally been used for food, forage, and firewood production by Southwestern Indians who considered mesquite's importance greater than that of corn and wheat. Unripened and ripened pods and seeds were eaten by humans and animals, and the wood continues to be prized. There is evidence that selected varieties of mesquite could become nitrogen-fixing, low water-using crops which require little or no tillage (11). Big sagebrush is also commonly regarded as a noxious plant because it is aggressive and unpalatable to domestic livestock. For these reasons it has been the target of widespread eradication programs. An alternative approach would be to use the richly variable germplasm base to improve the species' forage qualities.

An integrated management approach can also be used for noxious animals, but wild horse and burro control represents a particularly difficult problem. These animals are without effective predators and are capable of rapid population increases. They can inflict heavy damage on rangelands. Both offsite and onsite effects on water resources have been noted but never quantified (20). Transplanting animals is only a temporary solution, fertility-control with drugs is expensive, and selective killing is sometimes strongly opposed by the public.

Animal Mixtures on Rangelands

INTRODUCTION

Different animals have different food preferences, i.e, they consume different plant species, different parts of the same species, and the same plant parts growing at different heights. Therefore, mixtures of animals use resources more fully than any one species. When species more adapted to dry conditions are included, they may also use resources more sustainably.

ASSESSMENT

Some experts feel that animal productivity can be increased by stocking rangelands with more than one kind of animal (10). For example, new combinations of livestock and wildlife species could double range productivity in some areas, and an optimal grazing management scheme for shortgrass range sites might allocate forage to cattle (67 percent), bison (20 percent), sheep (12 percent), and antelope (1 percent) (17). Sheep and goats graze over wider areas and rougher terrain than do cattle. Used in combination, they could control brush and weed invasion resulting from overgrazing by cattle.

Few range managers have attempted operations of this complexity. Ranchers with private lands—e.g., in Texas—have the most experience with large mixtures of animal species. These mixtures usually include unusual exotic animals that are stocked for recreational hunting or photo safaris, not for large-scale meat production. This concept awaits full-scale testing with North American game and domestic animals.

Optimal combinations of herbivores can only be determined if the diet-selection process is understood. Currently, no models exist that can define this process and it is not possible to predict dietary or spatial use of any given site. The limited numbers of experiments with mixed-species grazing systems do not provide information on their long-term effects. For example, little is known about the effects of such systems on overall efficiency of energy use or of nutrient cycling. Furthermore, little is known about the effects of larger numbers of sheep on populations of big game animals.

When more than one species of animal grazes an area, it is critical to match demand to available vegetation. Overlapping plant preferences could destroy a plant species before the process is apparent in declining animal health or numbers. Innovative approaches are needed to study the responses of mixed animal

Box AA.—Alternative Agriculture in Arid/Semiarid Lands: The Innovators

It may be decades before alternative agriculture is practiced widely in arid and semiarid lands. Pioneers are at work now, and it may be their work that shapes the future of American agriculture.

Workers at the Land Institute in Salina, Kans., are developing a grain-producing system that mimics the diverse and productive grasslands which once flourished on the Great Plains. They use perennial plants to decrease tillage and erosion; legumes and quickly decomposing composites to cut fertilizer needs; and unusual germplasm to increase nutrition and seed yield.

Cooperative studies between botanists at the Arizona-Sonora Desert Museum (Tucson, Ariz.) and the University of Arizona explore the potential for crop mixtures of short-lived desert plants and perennials. Native plants such as mesquite, tepary beans, gourds, devil's claw, and cacti are blended with biological technologies for fertilization, pollination, and soil-water absorption.

The Agroecology Program at the University of California, Santa Cruz, focuses on research and small-scale field trials of new systems. Experiments include ones on integrated pest management, pollination, multiple cropping, the use of fire in agriculture, trees as crops, farm pond aquaculture, and composting. Part of this program is tailored to students, but it also includes cooperative projects with local farmers and extension agents.

Rodale Press has been a leader in the alternative agriculture movement and, with the establishment of the Rodale Research Center, it produces careful and credible agronomic research. This center, especially through its work with grain amaranth, is now working more with crops for dry lands. A new consulting role in foreign arid lands can be expected to strengthen these aspects of its program.

species on different types of range sites, especially where sustained productivity of wild and domestic species is the goal.

The combination of domestic livestock—e.g., sheep and goats with cattle—has not been practiced extensively. The sheep and goat industries are both relatively small, providing a limited market for new technologies and constraining innovation. The sheep industry, after a sharp decline due to low returns, high labor requirements, and losses to predators, seems to be at the beginning of a modest recovery owing to increasing competitiveness of natural fibers. Both sheep and goat producers face strict regulations that favor cattle producers.

Alternative Agriculture

INTRODUCTION

The predominant agricultural systems used in the arid and semiarid parts of the United States represent a fraction of the kinds of systems available worldwide. Present systems are largely based on frequent tillage; the use of a few, very specialized, annual crops; and additions of large amounts of added synthetic fertilizers and pesticides. While these systems predominate, some Western farmers do not use them.

Some farmers and ranchers are experimenting with types of agriculture that are quite different. These new systems are diverse and may include complex mixtures of crops in one field (polyculture or intercropping); they may include perennial grains or tree crops instead of annuals such as corn, sorghum, and wheat (perennial polyculture or permaculture); or they may eliminate synthetic pesticides and commercial fertilizers (organic farming). Generally, they rely heavily on natural biological processes, such as nitrogen fixation by legumes, instead of artificial replacements, like fertilizers (table 81).

ASSESSMENT

Such alternative agricultural systems have demonstrated their usefulness under certain conditions. Some scientists observe their in-

Table 81.—Examples of Human Substitutions for Biological Processes

Biological process displaced	Nonbiological process substituted
Natural fertilization in plants/seed dispersal	Plant breeding/harvesting of seeds
Fixation of atmospheric N by bacteria	Application of artificial nitrogenous fertilizers
Exploration of soil by roots for potash and phosphorus and water	Application of artificial fertilizers; irrigation
Natural control of pests and weeds	Use of pesticides and herbicides
Collection of feed by animals	Harvesting, processing and automated provision of compounded feed; forage conservation
Grazing	Zero-grazing (the cutting and carting of herbage)
Natural deposition of excreta on the land	Collection of excreta from housed animals and its disposal, treatment or distribution on land
Incubation of eggs by hen birds	Artificial incubator
Natural service by male animal	Artificial insemination
Natural hormonal processes	Control of light, day-length and temperature; use of synthetic hormones
Natural suckling (of calves and lambs)	Artificial rearing on milk substitutes
Natural immunity to disease in animals	Use of vaccines
Use of animal power	Use of machines and fossil fuel

SOURCE: C. R. W. Spedding, J. M. Walsingham, and A. M. Hoxey, *Biological Efficiency in Agriculture* (London, U.K.: Academic Press, 1981).

creasing credibility and expect that they will assume greater importance in the future (23). The advantages claimed for these systems are many and include lower use of expensive, fossil fuel-based chemicals that may be hazardous to human health and the environment, improved soil structure and better growing conditions for plants, less soil erosion, a more diversified and therefore more stable agricultural base, more nutritious agricultural products, and more efficient use of natural resources.

Some of these claims have been substantiated. For example, farms producing a variety of products generally reduce their risks and increase the effective use of total resources. Polycultures of plants grown together, in contrast to monocultures of one plant, may use soil nutrients more efficiently, increase economic returns, improve the nitrogen status of crops when legumes are part of the mixture, and provide stability of yields over time (16). Systems that eliminate synthetic chemicals also eliminate the possibility of pesticide contamination and minimize contamination of ground water and runoff from commercial fertilizers (21). Organic farming has been shown to increase wildlife populations and in at least one Western State, the U.S. Fish and Wildlife Service recommends it for producing crops for wildlife (29). Other claims, such as the effects of organic farming on crop nutrition, are less well understood and many need further research.

The earliest advocates of these technologies based their arguments on ideological grounds or on the perception of severe environmental problems resulting from traditional agricultural practices. More recent practitioners are adopting alternative systems on economic grounds. For example, most of the cornbelt/Great Plains organic farmers surveyed by Strange (29) cited the importance of lower production costs and insulation from rising variable input costs. One-fourth of these farmers borrow no operating capital. Many of these people also share a belief that farmers and ranchers should not exhaust the natural resources on which the future of agriculture depends. For this reason, they feel that alternative agricultural systems are among the most forward-looking and resource-conserving of technologies under development.

Both basic and applied research on alternative systems have been limited. This research is not simple: controlled experimentation is difficult, no one type of alternative agriculture is representative, and the benefits claimed to accrue may take decades to manifest themselves. Public and private investment in research is small. For example, USDA formally decided to terminate research in this area contrary to the results of its own study (35). Interested farmers have had few places to get information. One survey of organic farmers showed that only 5 percent sought or received help from land grant universities and only 3 percent could find assistance from extension agents (29). A more extensive foreign data base exists for some technologies, such as the polycultures of India, France, and Africa, but this information generally has not been adapted for use in the United States.

Research is lacking also on alternative systems for arid and semiarid lands. For example, most research on organic farming has been done in humid regions of the United States. Polyculture systems, such as those extensively used in India, are more common in arid regions and they generally perform better in dry seasons. But claims that polycultures use water more efficiently or are able to tap water unavailable to monocultures have not been substantiated. For these reasons, it is impossible to predict under what site-specific circumstances polyculture will prove to be advantageous.

This lack of information has contributed to an absence of organizations to assist producers with questions and problems related to alternative agriculture. The people who are interested in many of these systems generally are not part of the traditional agricultural community and are not well organized among themselves. Therefore, knowledge of alternative agricultural systems has had limited acceptability and visibility. There is evidence that the tendency to dismiss new systems as impractical or bizarre may be declining. For example, under a congressional mandate*, USDA completed its first study of organic farming in 1980, and the University of Nebraska holds an annual organic farming field day. Large numbers of farmers continue to express their interest in alternative methods despite the lack of official encouragement.

It is not clear yet to what extent these technologies will be applicable to farms or ranches of varying sizes and in different geographic locations. Most of these systems are highly integrated and require good management skills, substantial knowledge about plants and animals, and marketing expertise. The need for these skills may place low limits on the size and scale of a particular enterprise. While the productivity of some farming systems may be high per unit of land, the labor intensiveness may make productivity per farmer or rancher relatively low.

There is no consensus whether these systems would produce, in the near term, yields as large as those currently achieved. For example, some experts feel that the widescale adoption of organic farming would result in lower, but acceptable, total productivity (4). Other results indicate that adoption of organic farming practices might actually increase farm unit production by decreasing operating costs. The greatest benefit of these systems is in sustaining or improving inherent land productivity. This benefit could compensate for short-term yield reductions if they materialized (33).

Multiple Use of Croplands

INTRODUCTION

Rangeland uses for recreation and wildlife are important adjuncts to meat production in many areas. Similar multiple uses of cropland are possible, and some farmers are actively pursuing this option. In fruit, nut, and vegetable growing areas, some farmers invite customers to pick their own produce. Farmers may provide other services, such as hayrides to fields or samples of processed produce. Management of some areas emphasizes, for the visitor, the recreational aspect of the visit.

Grain-growing areas provide important wildlife habitats and some States allow leasing them for hunting. In Texas and California especially, irrigation and cultivation practices can sometimes be managed to increase wildlife habitat. The large pheasant and waterfowl populations that often result provide an opportunity for farmers to lease land at attractive prices.

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*Section 1461 of Title XIV of the Food and Agriculture Act of 1977 (Public Law 95-113).

ASSESSMENT

It is difficult to assess either the present or potential role of multiple uses of cropland. No central source of information exists on these land uses. For some areas, though, it is clear that wildlife and hunting uses of cropland are having a large economic impact.

Wildlife in many areas have suffered from recent agricultural practices. Fencerow-to-fencerow cultivation, removal of grain stubble, intense grazing of pastures, and extensive weed and pest control have adversely affected wildlife. These practices partly reflect the drive for higher agricultural production and partly the feeling that wildlife is a farm liability. Thus in some areas, recreational use of cropland is unlikely in the face of negative attitudes. Hunting on croplands is also limited by farm schedules. Hunting season may occur during harvest or other busy times when it is not practical to have visitors in the fields.

In other areas, agricultural practices have enhanced wildlife, and farmers have welcomed and used this increase (table 82). In South Dakota, small-game hunters purchase a $5 wildlife stamp in addition to their hunting licenses. The revenues generated are then paid to landowners for the maintenance of pheasant nesting cover. More than $500,000 was paid in 1979 to farmers at an average rate of $22/acre. After 5 years in operation, 535 landowners are involved and about 15,000 acres of cropland have been diverted for wildlife purposes (1). Some wildlife species do not benefit from such programs: in areas in which land conversion among rangeland, cropland, and pastures occurs, only those animals adapted to changeable conditions are favored.

Table 82.—Gross Revenue to Western States[a] From Hunting and Fishing Licenses in 1981

State	Hunting licenses ($)	Fishing licenses ($)
Arizona	—	3,585,167
California	7,005,827	24,156,555
Colorado	18,370,746	5,436,643
Idaho	5,322,771	3,100,745
Montana	4,688,759	3,797,090
Oklahoma	4,564,625	4,144,402
Oregon	7,543,558	6,408,517
Texas	6,314,663	7,406,271
Utah	5,598,120	5,129,323
Washington	5,867,014	6,704,656
Wyoming	10,919,365	—

[a] States included rank among the top 25 in the United States in terms of State revenue from these activities.

SOURCE: U.S. Department of Agriculture, Soil Conservation Service, "Texas Conservation Tips," December 1982.

Set-aside programs for wildlife are expensive to the organizers and may not encourage wide participation. The multiple use of farmland, therefore, depends on strong economic incentives for individual farmers. This is the case when croplands are leased for hunting. In Texas, for example, farmers are being encouraged to consider pheasants as a cash crop and to plan management decisions to accommodate gamebirds. By planting wheat, sorghum, and corn to provide cover and food in proximity to water, farmers can enhance pheasant production. Ponds that capture irrigation water runoff also have become prime pheasant habitat where farmers can encourage the growth of important gamebird vegetation. During hunting season, these practices translate into leases to individual hunters or sports clubs at a minimal cost of $25/person/day or $125/person for the season's opening weekend (28).

In Texas and other States where irrigation has changed the face of agriculture, the availability of water supplies may determine the future of both agriculture and wildlife. Changing water use in the Central Valley of California has had major effects on wildlife and has made hunting an important use of irrigated land. In many cases, the changes in in wildlife habitat or populations inadvertently accompanied changes in agricultural technology.

Table 83 shows some of the more general interactions between technological changes and resources in the Sacramento Basin of California. Specific changes may also be traced. In fewer than 100 years, about 5 million acres in the Central Valley were converted from grasslands, marshlands, and waterways to high-value farmland and urban areas. As a result, a number of species of waterfowl have become dependent on cultivated cereal crops, whereas other species dependent on the natural vegetation have declined. Pastures and fields of corn, rice, milo, wheat, and barley provide habitat for large numbers of migratory and resident

Table 83.—Relationships Between Agriculture Practices and Fish and Wildlife, Sacramento Basin and Delta-Central Sierra Hydrologic Study Areas

Practice	Opportunity for water saving	Agricultural viewpoint		Fish-wildlife-recreation viewpoint		Comments
		Positive	Negative	Positive	Negative	
Increase ground water pumpage	Possibly very large	Farmers gain operating independence and dry-year flexibility	High initial cost; big energy user	Reduces diversions from river	May increase percolation	One of two true means of saving water in basins
Increase reservoir storage	Moderately large	Increased dry-year supply	None	Decreases peak flows; increases dry-year summer flows; enhances reservoir-type fisheries	Would flood out native lands	Opportunity for true in-basin water savings
Reduce water applied to rice	Large, possibly several hundred thousand acre-feet	Should produce a large net saving in applied water use; save energy and fertility	Would increase irrigation management costs; increase TDS of drainage water	Would tend to reduce diversions from the Sacramento River, leaving more water for in-channel use	Would decrease drain flows, hence diminish riparian vegetation and fish flows, increase TDS and water temperatures	No savings would result unless storage provided
Level all rice paddies, form rectangles	Included above	Would decrease applied water use by an estimated 5%; increase yield, reduce water management and harvest costs, increase net profit	Would take land out of production for one crop year; require capital outlay	Included above	Elimination of berms would reduce wildlife habitat	Now catching on rapidly in rice-growing areas
Drain wet mountain meadows; improve water management	Small	Would reduce water use; increase forage production	Would require annual maintenance cost; high original investment	None	Would reduce wetland habitat reduce late summer downstream flows	As time goes on, practice will be employed through the incentive to increase forage production
District practices; canal lining (reduce seepage); increased use of relift pumps, control ditch bank vegetation, clear channels	Large, could reduce district demands	These practices will decrease water demands on a district basis; could increase yields and decrease fertilizer needs	Would require more energy, capital, and manpower, increase the unit cost of water, leave drain water users with no available supply	None	Would reduce wetland habitat, reduce fish flows, raise water temperatures, increase TDS, concentrate pesticides, and increase channel velocities in some areas	Must develop incentives for districts to take action; must persuade people that water-saving practices are necessary

SOURCE: State of California, Department of Water Resources Bulletin No. 198, May 1976.

waterfowl. In some parts of the valley, farmers can realize significant economic returns from leasing hunting rights. These farmers may flood cornfields and create wetlands instead of planting a second crop to increase waterfowl populations. In some cases, this practice also removes salts that have built up in the soil from previous irrigations. A large number of duck clubs now makes use of these croplands. For example, at least 84 private duck clubs exist in San Joaquin County, Calif., and about one-third, or 12,000 acres, of the land leased for hunting represents flooded fields.

In other areas, irrigation water is becoming less available, and careful management is undertaken. For example, where rice is grown, land leveling—the use of fewer levees between fields—and more productive rice varieties have increased yields but decreased both cover and food for wildlife. In these areas, wildlife populations have declined. Some experts feel that the situation is becoming critical. Greater pressures for careful irrigation management are driving farmers to use less water, and they cannot be expected to continue to sustain large water-dependent wildlife populations.

Computers and Information Management

Introduction

Ranchers and farmers manage information daily. Decisions regarding which crop to plant or when to sell livestock, for example, are based on obtaining and evaluating information from a variety of sources. The availability of electronic computers has changed the nature of information management, and computers are rapidly becoming everyday tools in agriculture.

Agricultural scientists have used computers for research analyses for some time. The direct availability of computer-assisted analysis to ranchers and farmers is more recent. Computers are having an impact in two different ways:

1. university/State extension services are providing access to large, shared computing facilities through networks of terminals; and
2. producers are purchasing microcomputers for home use.

The large computer systems share central data storage and processing facilities. The Agricultural Computer Network (AGNET) is a good example. AGNET was developed by University of Nebraska scientists in the 1970's and expanded into five Western States on a pilot basis in 1977. As of 1980, six States are full partners in the operational system: Montana, Nebraska, North Dakota, South Dakota, Washington, and Wyoming. AGNET relies on a large central computer in Nebraska and the backup skills of nearly 20 computer specialists in the participating States. Extension Service offices and individual users gain access via local terminals to program libraries. These terminals can be as simple as touch-tone telephones or as elaborate as nonportable terminals with video screens and printer attachments.

AGNET was designed to be a tool for making farm and ranch management decisions and for providing up-to-the-minute market news and extension information. Over 200 agricultural programs are available now to users and it is considered to be the best system available to farmers and ranchers today. Programs include ones for cattle production, tax planning, machinery costs, home food preservation, irrigation scheduling, and soil loss. Farmers and ranchers are often included in planning these programs to ensure their usefulness.

Microcomputers (also called home or personal computers) can provide some of the same facilities. These units often have a keyboard, a video or television screen, magnetic data and program disks and disk drives, and a printer. They are self-contained and often users rely on programs developed for their particular machine. Farmers and ranchers use these small systems for business accounting as well as for storing and analyzing records of herd performance. Some microcomputers have graphics programs for displaying the results of analyses. Telephone couplers allow microcomputers to be used as terminals and provide access to the large computer systems.

Assessment

Some experts predict that computers will become commonplace during the 1980's and that the farmers and ranchers who do not use these management tools will be out of business by 1990. Computers make recordkeeping more precise and can help prevent management errors. Both of these elements are crucial when profit margins are low and prices fluctuate widely.

Farmers and ranchers with timely access to large systems such as AGNET can use elaborate computer technology at minimum personal cost. They can use tools that were specifically designed for agriculture and many that were tailored to conditions in the West.

Costs for direct terminals into large systems such as AGNET vary from minimal monthly telephone rental charges to $7,000 for the most elaborate purchased ones. Several small portable terminals cost about $1,500. Also, users pay long distance charges for the time during which the computer link is actually made. These charges may increase operating costs beyond the initial purchase price of the microcomputer. Purchase and operating costs are usually borne by universities and cooperative extension services in order to make terminals available in county offices and for specialists to use for local demonstrations. Some extension offices supplement large computer systems with microcomputers and are developing special agricultural programs for them. For example, Utah State University is developing irrigation programs for their Apple microcomputers.

Agriculturists who rely on their own microcomputers will have fewer tools with agricultural applications immediately available. Telephone couplers into the larger systems are probably necessary to have adequate agricultural programs. Such linkages provide the best of the small and large systems, but they are far from routine now. Microcomputers that are sufficient for agricultural applications cost $4,000 to $5,000 for the machinery, or hardware, and an additional $2,000 to $3,000 for programs, or software. The more elaborate and expensive microcomputers also are more flexible. They are faster and easier to use, and their standard features allow hardware and software "extras" to be exchanged among different brands.

Photo credit: USDA-Agricultural Research Service

Replacing the driver? Agricultural engineer Robert Schafer presents tomorrow's farmers with the circuit board from a computerized guidance system for tractors and other farm machinery. Research shows that computer-controlled traffic across croplands can reduce soil compaction considerably

The trend to greater reliance on computers in agriculture has begun despite the substantial costs involved. A number of vital institutional issues remain to be resolved, including: 1) the role of the Federal Government in technology R&D, 2) the role of Federal and State agencies in training, and 3) the need for improved cooperation among various agencies. These issues may redefine the role of the Cooperative Extension Service, alter the audience which it serves, and determine how widely Government-developed computer technology is distributed. For example, some experts think that some extension services lag behind vocational schools and even behind some high schools in providing computer training.

Will Western agriculture participate fully in the computer "revolution?" The technology is available, but evidence suggests that Western farmers and ranchers have trailed Midwesterners in its adoption, perhaps by as much as 10 years (15). It is clear that some computer applications can contribute to greater efficiency of water use. But computers can also be used as irrelevant and expensive toys; such uses will not necessarily help solve difficult water problems.

CONCLUSIONS

Agricultural management technologies that affect water supplies in the arid and semiarid region represent a wide combination of individual practices, including animal and plant management, irrigation water management, cultivation practices, and computer and information management. Each of these management technologies is used in recognition that water is part of the natural system in which it is impossible to affect any part without affecting another.

Management technologies have high potential for maximizing production from available water, plant, land, and animal resources in the arid and semiarid region. Their application and significance in the future will depend to a great extent on research efforts by the scientific community, on economic costs and benefits of application, on managerial abilities of producers, and on decisions by policymakers at the local, State, and Federal levels.

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Chapter XII

Issues and Options for Congress

Federal support of Western water-resource management and planning is critical for that region's agricultural and economic development. Most of the West's water-resource problems are at least regional in scope and extremely difficult in nature, involving a complex web of physical, chemical, biological, economic, legal, and sociopolitical issues. Often, they go well-beyond the ability of a single Federal agency, State, university, or group of organizations to address effectively. Although Western State Governments have increased their role in this area, they cannot, by themselves, handle all the problems.

Because water does not remain within State boundaries, water-related activities in one State may have consequences beyond that State. Strong Federal involvement under the Clean Water Act continues to be needed to assure a high quality of Western waters as they pass through a river basin or an aquifer from one State to another. Federal funding and support in cost-sharing arrangements remains important for those regional water projects that require substantial investments, including those related to rehabilitating existing projects. Federal support for research in water resources and water-resources management continues to be needed to ensure that short- and long-range national interests are served. In addition, longstanding Federal obligations in reserved water rights, especially for Indian reservations, and in international agreements involve issues that require Federal attention. Finally, carefully designed Federal incentives should still play a role in helping States and individuals explore and develop effective water management planning and equitable problem-solving of water-use conflicts.

Congress, however, cannot act alone to be effective in this complex and diffuse area. Federal, State, and local governments are all involved with the regulation of Western water for agricultural and other uses. This involvement affects and guides use and development of water-related technologies for arid/semiarid agriculture. The broad types of Federal tools available to influence research and use of these technologies include developing goals and priorities for Western water use and agriculture, providing incentives, penalizing abuses, promoting improved management, equitably resolving conflicting claims and demands, and providing more and improved information.

The following policy issues have been identified by OTA as those requiring congressional attention and action over the next few years to further the goal of sustainable agriculture in the West. They are grouped in three major categories (treating renewable resources as systems, sustaining long-term productivity, and involving users in decisionmaking) and are not listed in any order of priority.

TREATING RENEWABLE RESOURCES AS SYSTEMS

This major action area is divided into three categories:

1. How Western scientists, water users, universities, and the public-at-large can play an increased role in decisionmaking about water and Western agriculture.
2. How congressional decisionmaking can be strengthened.

3. How other Federal and State Government agencies can improve specific programs.

Issue 1: The Need for an Interdisciplinary Program of Basic and Applied Research on Arid/Semiarid-Water Resources

Federal attempts in the 1960's and 1970's to build broad-based national programs in water-resources research and management through the Water Resources Council and the Office of Water Research and Technology were substantially reduced in the 1980's. Awareness of growing Western water problems has increased at a time when the Federal role in coordinating water-related research across the Nation has in large part been eliminated.

Many of the Nation's universities have research programs on problems of water resources or water-resource management. Representing a wide variety of approaches and focuses depending on their funding priorities, these programs involve a range of the natural and social sciences and engineering. Frequently, agricultural departments within the land-grant schools utilize cooperative USDA-State experiment station arrangements. Other universities outside the land-grant system or other nonagricultural departments in land-grant schools may conduct their work without cooperative USDA arrangements.

University programs related to water resources include biological and geochemical research on water quality; studies of ground water hydrogeology, recharge, and contamination; studies of wastewater treatment and reuse; studies of weather modification; research on interbasin transfer and on more efficient use of water in agriculture; and studies of the economic and legal aspects of water-resources management. These efforts include laboratory and field research as well as theoretical studies. They entail use of any array of field-measurement devices, computer modeling, or analytical instrumentation, or a combination of the three. They are housed in many different departments, colleges, and institutes of the universities, often appropriately in a number of sites on a single campus, depending on the focus and approach being pursued. All such programs have at least one feature in common; they are all directed toward developing new insight into the region's and Nation's water supply.

However, the present situation lacks national coherence. No mechanism exists for coordinating water-related basic and applied research as it might apply to the wide range of water-resources problems in the U.S. arid/semiarid lands. Often, links are not made to the broader national or regional public policy relevance of individual university research efforts.

A mechanism is needed that will focus the multiplicity of university water-related research approaches and disciplines on Western and national water problems. Progress in Western water-resources research, both basic and applied, will benefit substantially by the creation of a mechanism to focus and coordinate the talents of the Nation's universities, the research experiments of the innovative farmer and rancher, and the resources of the private sector.

Option: Establish a National Center for Water Resources Research

Congress could establish a National Center for Water Resources Research to provide a coherent and coordinated mechanism for the Nation's university research programs in water-resources management for problem-solving and policymaking. The mission of this center could include:

1. Undertaking an interdisciplinary program of basic and applied research on water resources and water-resource management. In addition to research in the natural sciences and engineering, the program should include a strong component of basic and applied research in the social sciences, such as resource economics and law as they pertain to water-resources programs. The center could further assist in

the conduct of site-specific research being carried out under State auspices.

2. Developing and providing advanced and sophisticated research facilities on a scale required to cope with the broad nature of water-resources problems, and often not affordable by single universities, to be used both by the resident staff, innovative producers, and university scientists.
3. Undertaking a program to develop and test conventional and emerging technologies for application to water-resources problems in U.S. arid/semiarid lands, including application to problems of agriculture and its sustainability in arid/semiarid lands, and coordinating work with existing Government research by USDA and State agricultural experiment stations.
4. Serving as an objective, nonpartisan, and continuing national source of information for Congress when formulating public policy dealing with water resources, and as a link to public agencies and to the private sector for application of research findings.

The center could serve as a base for marshaling the talents of the Nation's universities and for augmenting, but not in any sense competing with, the work already underway in the universities. Its principal function could be to enhance the effectiveness of water-resources research and to focus the full competence of the scientific community, private sector, and innovative producer on problems of water resources.

Using the example of the National Center for Atmospheric Research (NCAR), an institution created some 20 years ago by an act of Congress, the center could be managed and operated by a consortium of universities with doctoral-level programs in water resources. The member universities could elect a board of trustees from member universities, industry, user groups, and the community at large. The board could be responsible for establishing broad policy guidelines, for setting program priorities and directions, and for overseeing the center's effective management. The operation of the center could be directed by a scientist appointed by and accountable to the board of trustees.

Because a sustained effort is essential for solving crucial water problems of the West and the Nation, the funding support for the center must be stable and long term. The principal source of support for the center could be the Federal Government, with supplemental support from the States and private sector.

An equally essential aspect for effective operation is that prime responsibility for program initiatives reside with the consortium of universities managing the center. This requirement is in sharp contrast with "Government-owned, contractor-operated" laboratories where program initiatives often reside in the sponsoring, mission-oriented Federal agency. This contrasting approach for the center is important since the university community is closest to research for purposes of evaluating progress and potentials. In light of this knowledge, plans and priorities designed by the consortium could take into account national, regional, and State needs. Congressional and State agency staff could be assigned periodically to the center to translate research results for policymaking and update researchers on ongoing policy debates and issues.

For purposes of administration and funding, the center could be operated by the university consortium under a prime contract arrangement with a semiautonomous scientific agency such as the National Science Foundation (NSF). Support from other Government agencies interested in water resources could be arranged through the single contract administered by the designated agency. The style of research program management proposed above is consistent with the research-overview style and experience of NSF.

Issue 2: The Need for Congress to Have Reliable Ongoing Information About the State of the Nation's Renewable Natural Resources

OTA found that existing data available for congressional decisionmaking is scattered throughout the Federal Government in a variety of forms. These data were not collected with the intention that each piece would be part of an integrated and self-consistent base for Congress to use in making decisions affecting resource sustainability. Moreover, existing data on components of the resource base on which agriculture depends are seldom synthesized because the data may be in noncompatible forms and no single agency has had the ongoing responsibility to seek compatibility or synthesis.

Congress needs improved information for setting near- and long-term goals for sustainable use of Western water and agricultural lands. This information should focus on congressional needs and emphasize systems analysis of data about renewable natural resources.

A recent Federal study about the analytical capability of existing executive agencies to provide this long-term resource systems planning capacity concluded:

> . . . [E]ach agency has its own idiosyncratic way of projecting the future, based on its own responsibilities and interests. These different approaches were never designed to be used as part of an integrated, self-consistent system like the "government's global model." They were designed by different people, at different times, using different perspectives and methodologies, to meet different needs. While many are widely recognized as making outstanding use of state-of-the-art analytic procedures appropriate to their respective sectors, they produce projections that are mutually inconsistent in important ways.*

Ongoing analysis and synthesis of existing data bases could provide improved information on the dynamics of the resource system and how interactions (natural and manipulated) among resource components affect the sustainability of Western agriculture. Congress needs improved information to understand:

1. the extent and quality of each resource component,
2. the amount and location of each resource being used,
3. how quickly and where each resource is replenished, and
4. how and what interactions among the components affect the sustainability of the system.

Option 1: Develop a special analytical unit within the legislative branch

Congress could develop a bipartisan unit within the legislative branch with the principal purpose to provide Congress with ongoing, quantitative evaluations of the state of the renewable natural resource system as a consequence of near- and long-term congressional policies. The unit's program should be interdisciplinary and multidisciplinary, with access to state-of-the-art computer facilities to conduct comprehensive data analysis and synthesis from existing data sources on specific topics requested by Congress. Such a unit could identify data gaps that are important to U.S. decisionmaking and that affect the sustainability of the renewable resource base. It would require the independence and flexibility to obtain and interpret data in a nonbiased fashion for the entire Congress. The following characteristics are important for this unit to function successfully:

1. objectivity;
2. bipartisanship;
3. ongoing capacity;
4. multidisciplinary and interdisciplinary focus;
5. access to existing public data sources;
6. best available technology to analyze and synthesize existing data quickly;
7. highly skilled specialists; and
8. a small, manageable size.

Specific organizational structure and legislative authority would have to be developed to meet the unit's defined purposes. The first step in considering this option might be a workshop of interested and involved congressional, executive, State, and local participants to examine existing problems, the history of other experience in data synthesis, and possibilities for

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The Global 2000 Report to the President, Technical Report, vol. 2, 1980, p. 454; report was prepared by the Council on Environmental Quality and the Department of State.

action. This workshop might be combined with the formation of a joint committee of members from relevant House and Senate committees to plan how to pursue and consider this option further.

This option will require ongoing communications among the many branches of Government to achieve an acceptable arrangement for the new unit. Some individuals within Congress and the executive agencies may question the value of such a unit for a number of reasons. In recent years, public concern has increased over the growing size of congressional staffs. This unit, though small, could be so criticized. Others may claim that existing agencies are competent and qualified to provide Congress with the resource systems analytical capability and that a small legislative unit will require new funding at a time when funds are in short supply.

Option 2: Establish an analytical unit within the executive branch

Congress could develop an executive branch unit as an alternative to that described in option 1 to provide ongoing quantitative evaluations for congressional decisionmaking affecting resource sustainability. On congressional request, this unit could coordinate, integrate, and interpret existing information—similar to that proposed under option 1 for the legislative unit—and report directly to Congress. Traditionally, Congress has turned to the executive branch for answers to fundamental questions involved with its policymaking. Existing executive branch agencies have personnel, equipment, and many data bases. Some career staff have experience in aspects of water- and agricultural-data collection and analyses. At least partial funding might be made available in the executive branch through redirection of existing funds from lower priority activities, as determined by Congress.

Possible disadvantages of this option relate to the ability of existing agencies to incorporate this function and to the nature of executive branch programs in general, as noted in the initial discussion of this issue. In recent years Congress has found it necessary to develop in-house expertise to supplement executive branch input in areas requiring integration of issues or verification and clarification of executive agency reports. Existing executive agencies lack the analytical capacity for long-term resource systems planning. The placement of this particular unit in the executive branch poses concerns about continuity. Programs and priorities in the executive branch change with administrations. A small new executive unit is unlikely to be in a secure position to provide objectivity, coherence, and continuity, essential requirements for an effective analytical unit. The current reduction in Federal support in water-resources planning and research at a time when Western States are facing increased problems is only one example.

Currently, no existing executive agency has the broad-based coverage of agriculture and water required to meet the needs of this option. Existing executive agencies commonly must compete with one another for budget and program approval, especially where responsibilities are overlapping, as in the renewable resource areas. Any executive agency given the task of providing ongoing quantitative evaluations for Congress about renewable resources will require strong powers to obtain prompt and ongoing cooperation from each agency with potentially relevant data and expertise.

Issue 3: The Need to Integrate Water-Related Agricultural Activities in Government Agencies

The complex interrelated Western agricultural and resource problems of today require an integrated approach to program research and implementation. Generally, however, the public sector agricultural and water-related community is poorly prepared for the demands currently being placed on it in arid/semiarid agriculture.

Over the past few years, Federal reduction in effort to integrate national water matters has left the Nation with mission-oriented agencies focused on their own particular responsibilities. Present Federal agencies in Western water and agricultural-related activities have isolated mandates and short-term remedies to parts of the problem instead of pursuing research, data analyses, and technological development with a long-term view of the growing interdependency of all processes. For example, the U.S. Geological Survey (USGS) has data on water supply and quality, but not always in a form available and useful for the more refined agricultural planning increasingly required in water-short Western regions. The U.S. Department of Agriculture (USDA) may conduct research on a particular water-related technology without linking the design and results to other important components of the onfarm process; e.g., plant drought and stress factors, soil-water management, or practices to reduce nonpoint source agricultural pollution. The Bureau of Reclamation storage and delivery projects may work from an engineering perspective but may not be responsive to the growing needs of contemporary farmers for more flexible and rapid adjustments to their water deliveries in order to "save" water onfarm. The National Weather Service may provide water-related forecasts in the West, but not in a context useful to the farmer who is planning crop-water requirements.

No longer can Western water-related agricultural problems be trusted to trial-and-error or one-problem/one-solution procedures that have been chiefly relied on in the past. Federal agencies charged with implementing congressional policies and programs need an integrated coherent approach that minimizes confusion in organizational responsibilities, and identifies technological impacts as they affect various components and ultimately the agricultural system and long-term productivity of the region. The following options are specific areas conducive to immediate congressional action, and all four are compatible with one another.

Option 1: Develop a USDA office of resource coordination

Congress, through the hearing process, could initiate discussions with USDA for the purpose of designing and establishing a high-level office to integrate and provide coherence to water-related and agricultural activities within the Department. This office of resource coordination should be placed at an appropriately high level, for example, in the Office of the Secretary of Agriculture, to ensure coordination and integration of activities among all specialized agencies of the Department. The purpose of this office would be to:

1. analyze the various agency goals, priorities, and funding for any overlapping or potentially conflicting activities related to sustainable agriculture;
2. integrate the resource work of the various agencies within USDA;
3. facilitate information exchange among agencies;
4. work to develop consistency and reliability among resource data bases of the various agencies;
5. advise the Secretary on program adjustments to ensure that the Department operates with an integrated-systems approach to agricultural research, technology development, and production; and
6. oversee the development and implementation of a systems perspective to specific agency programs, such as that currently in the planning stages within USDA's Agricultural Research Service.

The office could ensure that all departmental activities involving renewable natural resources are coordinated, alleviating the situation in which programs of one agency may work at partial cross-purposes with those of another. An office located in the Secretary's Office could emphasize the critical nature of agriculture's natural resource base and make visible the role of the Department in protecting it. It could encourage the Department to take advantage of the most modern systems-analysis technology, technology that has not often been used in agriculture.

Potential disadvantages exist with this option. An office of resource coordination within USDA might become isolated from the operational activities of the Department unless careful procedures tie it to the action agencies. Its role might vary widely among administrations, making important responsibilities susceptible to political ideology. Some agencies might view its activities as competitive with their own and not be fully cooperative.

Option 2: Strengthen water focus of Federal land-management agencies

Congress could instruct the Federal land-management agencies responsible for Western public lands to strengthen their focus on water resources and water-resources management as it affects agriculture, the primary Western water user, pursuant to their multiple-use responsibilities. As part of this effort, increased program attention could be paid to the mountain snowpack areas of the West, sources of significant surface water production for the entire region.

The multiple-use concept is already embodied in a number of Federal laws, including the Multiple-Use, Sustained-Yield Act of 1960 and the Federal Land Policy and Management Act of 1976. Existing multiple-use statutory guidelines prohibit optimization of single, measurable resources (e.g., timber and cows) at the expense of less quantifiable uses (e.g., watershed and recreation), and they forbid practices that impair continuing land productivity. In recent years, however, this mandate has often been dismissed in preference for more single-purpose mandates aimed at revenue-producing activity. For the U.S. Forest Service, this focus is principally timber production; for the Bureau of Land Management, grazing. Decisions related to these single-purpose goals have left inadequate resources for the kinds of research required to adequately take into account such primary values as water in their resource-management activities.

It is important that Congress take an increased interest in overseeing implementation of the broad, multiple-use mandates of these agencies. This option will entail a reorganization of agency priorities such that more emphasis is provided for long-term benefits from water management and less emphasis is provided for short-term revenue-producing benefits from grazing and timber production. To ensure that water-management issues are adequately addressed, such tools as water impact statements might be considered. Existing legislation might be strengthened, new legislation might be added, or oversight might be more earnestly focused on this increasingly important aspect of Federal public lands management—where possible, linking budget provisions to satisfactory performance.

An increase of focus on water resources by Federal land-management agencies could lead to a significant improvement in management of water use on arid/semiarid lands. The primary water-producing areas in the West, the mountain highlands, are on public lands. As competition for available supplies increases, Federal land-management agencies could play an important role in designing and implementing long-term water-management programs for the most effective use of water and in improving the knowledge of highland-lowland water interactions for arid/semiarid agriculture.

There are several difficulties in strengthening the focus on public land water resources. Federal agencies charged with this responsibility have no standards or defined priorities for planning and integrating water projects within multiple-use objectives. Multiple-use requires tradeoffs. Some uses cannot be maximized in a multiple-use system. A greater focus on water may require adjustments in management plans that result in some revenue reduction, from timber and grazing activities, for example. Moreover, a high proportion of agency personnel may lack the training and data needed in hydrology to make the complex planning and program decisions required to effectively integrate water into multiple-use programs. Finally, political influence and economic conditions have tended to set priorities favoring timber and grazing, in spite of the multiple-use mandates. Education of Federal administrators and new thinking are required for the Federal Government to appreciate the value of water in the long-range planning of public lands for arid/semiarid agriculture.

Option 3: Help States integrate water-resources data bases for systems planning

Congress could provide technical assistance and financial support to States for development of computerized water-resources data bases. A wide range of hydrologic data is presently being collected by various State agencies and private industries as part of resource-monitoring programs (e.g., of mining sites). A computerized data bank would make it possible for each State to store, retrieve, analyze, and integrate a range of data not now being entered into Federal data-storage systems, but increasingly needed for the depth of water planning required at the regional, State, and local levels for agricultural and nonagricultural purposes.

Such data bases could be designed to ensure integration of water quality and quantity data for water-resources planning. Federal funds to States for water-resources planning and coordination could be allocated for State participation in this data system. The private sector could share data and give advice on the best available technology for data storage, retrieval, and processing. Different States may need different levels of Federal technical support and financial assistance to develop basic facilities.

Difficulties in data availability and use may continue, even with the development of State data banks, without some shift in other related activities. For example, today in many Western States water-quality and water-supply responsibilities are assigned to different entities. To be effective, the development and ongoing use of data banks at the State level may require increased coordination and cooperation among the various State water-related agencies and increase in staff skilled in computer data storage and retrieval.

Option 4: Expand mandates of Federal agencies in instream flow matters

Congress could expand the mandates of the Federal agencies responsible for water-project development and maintenance to take into account needs of instream flow, an area that has had inadequate and, in recent years, reduced attention at the Federal level. The agencies could be directed to develop information and operational procedures to identify and address instream flow responsibilities and to be receptive to public concerns about instream flow issues. Coordination and consultation with other Federal and State agencies on instream flow matters could be systematized and intensified. Instructive scientific and lay publications on Western instream flow fluctuations and associated requirements to maintain the multiple purposes of each river system in the West could be an important aspect of these agencies' expanded responsibilities for instream flow matters.

The maintenance of instream flows may make it possible to maintain acceptable water-quality levels in some Western rivers without the need for greatly increased water-treatment facilities. An improved understanding of instream needs for the multiple purposes of Western river systems may also help improve management techniques to meet long-term requirements of hydroelectric generation and of fish and wildlife habitat protection. Without maintenance of some level of instream flow, the quality of the river, in effect, becomes the quality of return flows, which can often render a river unsuitable for subsequent uses without expensive treatment.

An increased Federal focus on the maintenance of instream flow requirements also raises difficult issues. Traditionally the Federal Government has deferred to the States on matters involving local water rights. In many U.S. Western river systems, virtually the entire river flow is already committed to various local offstream uses. If instream flow requirements are to be met on these rivers, some existing offstream uses might have to be curtailed or discontinued altogether in some of the most severely water-short areas. Over the long term, adjustments may prove the best approach hydrologically and economically. Over the near term, however, socioeconomic impacts may occur during a period of transition that may require special Federal assistance and attention to ensure that severe dislocations are minimized. Federal involvement will raise all the difficulties inherent in trying to coordinate and respect the two governmental systems concerned, the long-standing States' interests in local water rights and the broader geographic and national interests of the Federal Government.

SUSTAINING LONG-TERM PRODUCTIVITY

Issue : The Need for a Strong Federal Role in Water Quality for Sustainable Western Agriculture

Water-quality issues require broad geographic perspective and strong involvement by the Federal Government at a time when debate increases about the need to reduce Federal efforts in general. A strong national interest in water quality is fundamental to protecting the public health and environment in the arid/semiarid West. The Western region, with roughly one-third the volume of flow-through water as that in the East, cannot absorb the levels of industrial, municipal, and agricultural pollution that the East can. Because agriculture affects and is affected by water-quality degradation, the long-term economic development of Western agriculture will hinge on a strong national commitment to maintain high-quality standards, support pollution controls, and strengthen research efforts on the impacts of water pollution on agricultural and nonagricultural users. A concerted, focused program of water-quality maintenance and pollution control that involves the States is necessary.

The following options are compatible, and all could be adopted by Congress.

Option 1: Make a firm commitment to strong Federal water-quality standards

Congress could maintain a firm commitment, particularly under the Clean Water Act, to stringent national water-quality standards for all uses. National standards are fundamental for long-term economic, environmental, and public health protection of the Western States. Stringent national water-quality standards must be of high priority in order to protect the range of present and future interests in water, some of which require the highest standards (e.g., for drinking water). Existing requirements should be retained, and any new or revised water-quality standards should be made to enhance rather than degrade existing water quality.

The West must be especially protective of its water quality in view of the intensity of use and reuse throughout the region and of the gaps in knowledge about the complex interaction of surface and ground water systems. Congress could take special measures to minimize the opportunity for exemptions or waivers to high-quality water standards in the West. Even one waiver could result in contamination of a river basin or aquifer to such a degree that regional and national interests could be jeopardized.

Without the maintenance of high national standards, it is conceivable that agricultural production in some areas may decrease or cease because of water-quality degradation. This situation could have major local and national implications, depending on the severity of the problem, for local economics, national food production, and international trade. If water-quality standard-setting were delegated to the States, some upstream States might lower standards, causing downstream users the increased economic burden of absorbing higher treatment costs before the water could be used. National standards are needed to ensure that economic burdens and benefits are evenly shared among States and to avoid industrial "shopping" for areas where water-quality standards are lowest.

This option requires substantial commitment of Federal, State, and local staff and finances, all of which are becoming increasingly limited. Monitoring and enforcement costs are involved as is increased research on the wide range of contaminants likely to be present from time to time in Western water supplies.

Option 2: Implement nonpoint source agricultural pollution controls

Progress toward implementing nonpoint source agricultural pollution control programs is essential for the same reasons strong water-quality controls are generally needed in the West—the more concentrated contamination possibilities with any pollutant. Congress could revive national nonpoint source policy under the Clean Water Act and particularly section 208, and actively support the accelerated implementation of controls on water pollution from nonpoint agricultural sources where problems are arising. This could include documenting and monitoring attempts and successes in controlling nonpoint source agricultural pollution. Current knowledge has identified some control measures useful for nonpoint source pollution through the adoption of improved onfarm management practices. While more research will improve such understanding for even better control, current opportunities exist to reduce such pollution. Some of these practices may involve costs that are difficult for economically disadvantaged farmers and ranchers to absorb over the near term. However, such costs may be far outweighed by long-term social benefits in reduced water-treatment costs and public health problems and thus justify a Government role.

Because of limited resources, many States now rely on voluntary action and cooperation to achieve nonpoint pollution reduction. As part of its commitment to control nonpoint source pollution, Congress could direct that Federal support to State and local efforts be strengthened. Increased Federal support could come in a number of forms, including technical and financial assistance for training farmers and ranchers to implement control measures, providing incentives, and assisting economically depressed farmers to implement better practices. Federal grants to farmers might be made contingent on farmers implementing known procedures and methods, including "best management practices," to reduce such nonpoint source pollution. Federal agencies already involved at the local level could increase efforts to monitor agricultural runoff and assess methods of reducing nonpoint source agricultural pollution.

The disadvantages of this option relate principally to implementation uncertainties and costs. To ensure adoption of "best management practices," some economically disadvantaged farmers may need technical and financial assistance to prevent the added costs from forcing them out of business. Additional resources, including staff and funds, may be required to implement the program and to enforce it through surveillance and monitoring. Furthermore, to improve understanding and control of nonpoint agricultural pollution, continued research and analyses are needed on the hydrologic impacts of agricultural practices and on improved methods of pollution control.

Option 3: Increase research and monitoring of agricultural and health effects of contaminants in water

Congress could increase its support of research and monitoring on the short- and long-term agricultural and public health effects of various contaminants in surface and ground water, an area of research that is presently fragmented and has few regional syntheses of data. Present understanding of water-quality conditions in the Western United States is based largely on contaminant-specific local studies. Little research, including that on ground water contamination, has been undertaken on a comprehensive areawide basis or on related health and environmental impacts. Such research and monitoring could provide valuable information for national policymaking to protect ground waters and surface waters from contamination. Existing standards may not adequately protect the public in some areas, while others may be too stringent. Once contaminants and their long-term environmental and health effects are better understood, water-quality standards can be adjusted accordingly. In view of the West's low or sporadic water-volume flows, the prudent approach is to maintain high or stringent standards for both surface and ground waters and to support high levels of water-quality research to ensure long-term protection of public health and safety and of the environment on which agriculture depends.

This option will require the support and assistance of all levels of government. Much of the current information on specific contaminants and water-quality problems is with local and State environmental protection agencies, health departments, and universities. National synthesis and analyses of existing data and a strong national program of research will take the time and talents of health and environmental specialists throughout the country. It may be important to assist such efforts with funds and support facilities through such means as special grants administered by Federal agencies responsible for environmental or health-related matters. Duplication of effort may also be a problem unless a national focal point for coordination and information exchange can be designated and supplied with the necessary resources to function effectively.

Issue 2: Protecting and Maintaining the Long-Term Productivity of Rain-Fed Agricultural Resources

Protecting the renewable resource base for productive rain-fed agriculture in the arid/semiarid West is a growing concern. Western dryland and rangeland areas of the Great Plains, the intermountain States, and the Southwest are important for rain-fed agricultural purposes. Dryland farming sites represent unique, global, soil/climate resources especially suited for grain production. These areas are vast; three times as much land is devoted to dryland crop production in the West as to irrigated agriculture. Regional variations in climate exist, but dryland areas share two features: 1) a limited and highly erratic supply of water, and 2) a susceptibility to erosion. Sustainable agriculture in these areas must take both into account.

Similarly, rangelands represent a substantial Western land area and must be carefully managed to maintain productivity. The problem of cultivating rangelands has become particularly critical in the semiarid lands of the 10 Great Plains States, where vast acreages of grassland still exist, and in other States in the West (e.g., California and Arizona), where the land is particularly vulnerable to erosion. Such areas are generally unsuited for cultivation because they are either too arid or on soils too shallow or infertile to raise crops. Most rangelands are now in that category; they are unsuitable for cultivation but can produce, in an uncultivated state, forage for livestock and other important services, such as habitat for wildlife. Some Government programs currently carry incentives that encourage cultivation of arid/semiarid lands unsuited for cultivation but agriculturally valuable as rangelands in their natural state.

Maintaining and improving suitable rain-fed agricultural systems could increase resource productivity on vast amounts of U.S. land. Dryland and rangeland agricultural systems will likely increase in importance in view of uncertain water supplies for irrigation.

Since the following two options are compatible, both could be adopted by Congress.

Option 1: Withdraw Federal incentives for cultivation of Western lands unsuited for cultivation

Congress could withdraw Federal incentives that induce conversion of rangeland to cropland use where that use is not suitable for the resource. One method of achieving this could be to require that applicants for Federal agricultural assistance certify that their land is not new cropland or, if so, demonstrate that a conservation plan approved by the local conservation district is in or will be in place for the land put in production. The land-capability classes could be used as a guide for determining what lands are unsuited for cultivation and, thus, ineligible for Federal assistance unless approved conservation measures ensure that the land is not degraded.

Withdrawal of Federal incentives (e.g., price supports, commodity loans, and disaster payments) for those producers who convert marginal lands to cropland would have little impact on conversion during periods of high-commodity prices since less Federal assistance would be requested. Furthermore, withdrawal would not "undo" the resource degradation that has already occurred or may occur as a result of inappropriate practices on such lands. The option does not include provision for land rehabilitation; thus, a speculator would not be given the incentive to plow-up marginal lands with the expectation that assistance will be available for rehabilitation in the event of severe erosion.

Concern may exist about the feasibility of implementing this option. Implementation problems could include the difficulty of developing adequate conservation plans for those who wish to convert rangeland to cropland. Additional staff and data may be required not only to design adequate plans, but also to enforce the plans and monitor compliance. Some sites may not have had resource surveys; thus, information may be lacking on soil resources or other related water- and environmental-data needs that are important for making judgments about the feasibility of cultivation. Finally, even though the land-capability classification system may be the best tool generally available, it has many inadequacies, and questions exist about its reliability for assessing land-conversion issues. The National Association of Soil Conservation Districts, that has tried to address some of these practical issues regarding implementation, maintains that the attempt is still worth trying in view of the growing severity of the conversion problem.

Option 2: Direct increased attention to rain-fed agricultural technology research and development

Congress could direct USDA to increase its research and development focus on rain-fed agricultural systems—both rangeland and dry land. As Western water restrictions and costs grow, irrigated production of grains and other crops may decrease over time in many Western areas that can produce rain-fed crops. These areas may be well suited to production of stress-resistant varieties of conventional crops and of other crops that are not now domesticated or widely grown. Significant opportunities exist to develop and expand dryland and rangeland research into these broader areas of focus. Moreover, many dryland and rangeland areas could produce beyond their current capacities if a broader focus and strengthened support were given to some of the long-term opportunities of such technologies as water-conservation practices, land reclamation, integrated brush management, sophisticated range management, and other biological techniques that are based on the strengths of the natural systems.

One means of implementing this option could be to convert some existing USDA field stations specifically to facilities to test and develop technologies. Such research and development could be part of an integrated resource approach to sustain or improve long-term productivity of rain-fed agriculture in U.S. arid/semiarid lands. Congress could hold hearings with USDA to examine USDA's existing stations for the purpose of identifying those facilities most appropriate for conversion. Research results could be made readily available to ranchers and farmers through cooperation with other USDA laboratories, State experiment stations, extension services, pilot projects, field-demonstration days, and exhibits for the public. Grants might be provided to individual producers to test new technologies. Cost-sharing arrangements could increase emphasis on innovative technologies.

Some may argue against this option, urging that more and better crops for rain-fed agriculture may not be needed. However, that claim is valid only if large quantitities of "new" water become available to agriculture, an unlikely possibility in the foreseeable future according to the findings of this assessment. Others may argue that rangeland research will be unnecessary because red-meat consumption may decline requiring less forage for livestock. Finally, resources devoted to potential new crops adapted to low-water regions could decrease those available for growing current commodity crops.

INVOLVING USES IN DECISIONMAKING

Issue 1: Achieving Equity in Western Water Availability and Distribution

Lasting settlement of conflicts over water use in the arid/semiarid West must involve principles of equity and fairness. The Federal Government, acting as public trustee for Federal reserved water rights, is directly involved in water-equity issues in the Western United States. Without the application of equity principles in water distribution and development, perceptions of unfairness will exist, and conflict and litigation, already problems of serious proportions, will increase.

Water is security as well as opportunity in the West. Because of water's special properties as a dynamic renewable natural resource and a fundamental social good, it has always been subject to some public regulation to protect public interests. The practical application of equity principles to protect the social value of water has become a difficult test for contemporary institutions as rising demands have increased pressure on dwindling supplies. In light of growing conflicts over use, the need for Western institutions to ensure equity and fairness in decisionmaking on water distribution and reallocation is a growing concern for many users. It is especially worrisome for those rightholders who may not have developed their rights and for third parties who may be harmed by shifts in resource use or by resource degradation.

Option: Assume leadership role in directly addressing issues regarding Federal reserved water rights

Congress, in its leadership role under the Federal reserved rights doctrine, could increase its efforts to address the complex and long-term task of resolving issues surrounding Indian reserved water rights and how they can be protected in the future in view of increased competition over water. In particular, two initial actions are appropriate. First, increased opportunity could be provided for negotiation and ongoing representation of Indian interests in both Houses of Congress. This might be accomplished through a variety of approaches, including the initial appointment of a joint House and Senate commitee or a special task force to better define specific options for Congress, or the creation of a subcommittee on Indian affairs. Second, to protect reserved rights where States have already fully appropriated water, legislation could establish a mechanism to remunerate or compensate reserved rightholders for water being used by others and to provide for eventual reallocation of water to reserved rightholders.

Because Congress has consistently left these issues unresolved, piecemeal court decisions have increased uncertainty for all parties, and important Federal interests and economic investments have been threatened. In recent years, pressures have grown (due to both non-Indian and Indian needs) to quantify present and even future rights. Under the Federal doctrine of reserved water rights, Indians were promised use of adequate supplies of water to meet present needs and future opportunities. By the very nature of the rights, society has agreed to live with some uncertainty in order to protect Indian homelands, so long as the claims are reasonable. The Federal Government, as public trustee, has an obligation to fulfill these agreements and promises. Congress could act to ensure that the Federal Government adequately protects Indian interests by resolving issues surrounding reserved water rights through the types of actions mentioned above. This will be an important step in the effective long-term planning and development of sustainable Western agriculture.

Option 2: Establish a congressional committee to oversee the renewable natural resource interests of disadvantaged populations

Congress could establish a Select Committee on Disadvantaged People and Renewable

Resources to investigate and recommend legislation to protect the natural resource interests of disadvantaged populations. A particular focus for Western disadvantaged people, especially poor farmers and Indians, could be their relation to water resources. Among the topics the committee could address is a mechanism to educate these groups about their stake in water management.

In addition, the committee could investigate the possibility of legislation to help disadvantaged Western people form mechanisms to bargain collectively for Western water rights that might be bought or sold in a market framework. This kind of modification to "free" market economics with respect to public properties of water could help ensure that equity interests are represented in large water-market transactions. For example, large energy companies might choose to buy up major water rights. This shift in water use could result in major changes in economic patterns and in community life, along with severe dislocations for many of the residents, including remaining farmers. These changes may not be agreeable to some community members. Where such shifts are likely to precipitate community change with major lifestyle implications, equity principles would suggest everyone needs the opportunity to participate in decisions about how the water is to be used. The opportunity to participate fully and fairly requires that information be made available on ways to pursue lifestyles in spite of change as well as ways to participate in the transaction generating the change.

Congressional action on this option and the related prior option on Federal reserved rights will be a challenge politically and administratively. Competent, sensitive staff, flexible and creative negotiation, and a visibly strong national commitment will be required for a long-term effort if these complex areas are to be addressed effectively. Already, perceptions are growing among poorer farmers and American Indians that existing Western and Federal institutions responsible for water distribution and development have not always treated them fairly. Committed congressional action is needed on both options to overcome conflict and litigation, all of which will severely hinder secure water-resources planning and management for sustainable Western agriculture.

Issue 2: Understanding the Impacts of Water Pricing on the Adoption of Technology

Farmers and ranchers respond to economic conditions in their attempts to become efficient. Federal subsidies have lowered the cost of water for many Western users. When water is inexpensive, the use of large amounts of water may be efficient from the user's point of view but not from society's point of view, since society (the subsidizer) is paying for some of the individual's costs. Although farmers and ranchers have adopted more efficient technologies in recent years, they have done so generally for reasons other than water conservation, usually to reduce energy or labor costs. Water conservation, when it has occurred, has been a secondary benefit in most areas.

Existing Federal water-project repayment laws and policies are receiving increased attention and study. Reforms being proposed in both the legislative and executive branches include more equitable cost-sharing arrangements and greater cost recovery from the water users. Such reforms will have the effect of helping move the cost of water to a level more reflective of its scarcity value.

As the cost of water increases, some agricultural users may find it economically profitable to transfer (sell or rent) their water rights, especially those senior rights that may attract a high market value. Other agricultural users may adopt more efficient water-use practices to reduce total input costs, in view of higher water prices, and remain a profitable operation. The price of water in a water market may be affected by Federal action with water subsidies insofar as those subsidies affect the quantity of available water.

The short- and long-term consequences of greater market activity in Western water are matters of lively debate and growing concern, especially for some Western farmers. Water is a resource with physical characteristics and social value not suited to a pure market situation. Transfers of major upstream water rights could conceivably have hydrologic and economic consequences downstream. Moreover, questions exist about the desirability from a national standpoint of allowing water markets to develop without some measures to assure that existing agricultural users are not severely harmed and that long-term public welfare is benefited.

Option: Evaluate the impacts of water markets on agriculture and related economies

Congress could seek the assistance of the Congressional Budget Office (CBO) in a study of the short- and long-term economic impacts of reduced water subsidies and increased water-market activity on Western agricultural users and nonfarm economics. A CBO analysis can help Congress: 1) understand the possible near- and long-term economic consequences of reforming water-project repayment plans and programs for Western agriculture and nonfarm economies; and 2) provide guidance, monitoring, and assistance with the transition to greater use of water markets to the extent that is likely to result from reduced development subsidies. Although scattered studies are beginning to appear on the economics of water in the West, CBO could provide an objective, comprehensive synthesis of available socioeconomic information and a focused analysis of the Federal connection with the economics of Western water and agricultural practices.

Over the near term, an easier solution might be to allow the existing situation to continue. Gradually, however, water-related problems aggravated by competing demands will probably increase. Actions such as this option may help Congress deal with the changes likely to occur because of water-subsidy reform, particularly those changes in Western agriculture and in nonfarm economies affected by Western agriculture.

Issue 3: Improving the Effectiveness of Water-Related Technologies for Sustainable Agriculture

The bulk of current knowledge about the potential of existing and new technologies to contribute to a sustainable Western agriculture is from site-specific studies. These studies have led to the formulation of technological principles that may have general applicability. However, judgments about the potential of specific water-related technologies for sustaining arid/semiarid agriculture in the Western United States are difficult to make from these site-specific data. A principal reason for this is that the effective application of specific technologies depends on the ability of the researcher and user to adapt them to local conditions.

Moreover, the researcher's perspective about effectiveness may vary from the user's perspective; the former may be looking at technical efficiency, while the latter may be interested in economic efficiency. Research for both onsite and offsite technologies suffers from questions of relevance and practicality for a particular agricultural site and user.

Option: Provide mechanisms for increased researcher/user interaction

Congress could direct USDA and the Federal land-management agencies to establish user-oversight groups for their research activities in two particular areas. One user-advisory group could focus specifically on the onsite water-conserving technology needs of arid/semiarid agricultural producers and provide advice and oversight principally to USDA. Particular emphasis could be placed on identifying and using innovative producers representing the variety of agricultural systems in the West. Local agricultural organizations could be useful sources of information to identify the most innovative producers.

A second user-advisory group could focus specifically on the usefulness of offsite water-augmentation technologies for downstream agriculture. This user group could be comprised of innovative producers who are directly downstream from the experimental water-producing sites. The group could advise and oversee those Federal agencies responsible for water-related technologies that are applied upstream or in highland areas offsite from arid/semiarid agriculture but have potential water-related impacts for that agriculture (e.g., weather modification, watershed management, snowmelt forecasting). The linkage between researcher and user is particularly important with such water-augmentation technologies because resource manipulation often occurs some distance from the point of potential agricultural impact. A user-advisory group could provide researchers with the increased opportunity to understand downstream needs of water timing, quality, and quantity.

These user-advisory groups could report to heads of agencies and to Congress. They could provide the much needed perspective of the people who ultimately use the products of research. Such an approach could mimic the highly successful Israeli system in which agricultural researchers engage in farming and equipment manufacture as well as laboratory work. In view of the site-specific effectiveness of water-related technologies and of the focus of much of the Federal water-related research work in arid/semiarid lands, improved agricultural user-researcher communication could provide guidance to Federal agencies about priority areas for action. User groups could assist Congress in determining whether Federal resources in these areas are producing results that justify continued Federal support or whether a refinement in focus and programs is appropriate.

Concerns about this option relate to the possible effectiveness of the user groups. At present, a National Agricultural Research and Extension Users Advisory Board (UAB) exists pursuant to legislation in the Food and Agriculture Act of 1977. A recent OTA report on the U.S. food and agricultural research system found this board's effect on USDA research priorities to be unclear. Other concerns are that researchers who interact with user groups would be taking time that might be spent otherwise with laboratory or field work. Moreover, the focus of particular users might be on short-term economic solutions rather than long-range issues involved with the development of technologies for sustainable agriculture.

In light of these concerns, the task will be to define carefully and succinctly the composition and functions of the Western user-advisory groups proposed by this option. Precautions will be needed to ensure that such groups effectively represent Western users and have the capacity to evaluate and examine objectively the work of the Federal agencies. Congress could require that users be nominated by representative agricultural organizations and have access, when needed, to scientific expertise independent of that of the Federal agencies.

Appendixes

Appendix A

Features of the Arid and Semiarid Region

Note: The information in this appendix further elaborates on material presented in chapter II.

Natural Features of the Arid and Semiarid Region

The Great Plains

The Great Plains stretch eastward from the Rocky Mountains to the Midwestern United States in a band 300 to 400 miles wide and extend north and south from Canada to the Gulf of Mexico. The region features comparatively level, broad expanses of land that are, for the most part, easily traversed and readily habitable.

The climate of the Great Plains is highly variable, and its weather is known for extremes. Average annual precipitation generally increases from west to east and from north to south; greatest amounts occur during the spring and early summer. Amounts fluctuate widely between years and months but generally range from about 25 inches in southern Texas to less than 12 inches in the northern part of the Plains. Snow accounts for 20 to 30 percent of the annual precipitation in the central and northern areas of the region. Another apparent characteristic of precipitation is a tendency for a number of below- and above-average precipitation years to occur together.

Temperatures in the Plains tend to increase as one moves south. In the northern Great Plains, mean monthly temperatures for January and July are 5° and 70° F, respectively. In the south, average temperatures for these months are 40° and 80° F. Winter temperatures of −60° F and summer temperatures as high as 120° F have been reported. The length of the frost-free period ranges from about 100 days in the north to over 200 days in the south.

Wind is a prominent feature of the Great Plains. Over most of the area, average wind velocity is 10 miles per hour. However, in the winter and early spring, the region often experiences strong winds of 30 to 60 miles per hour that are sometimes accompanied by snow. The winds that occur during and after these storms may last for several days and cause severe soil erosion as well as damage to vegetation, livestock, and buildings.

Soil characteristics in the region vary widely, reflecting differences in parent sources, topography, climate, and plant and animal life. In general, soils of the Plains region are relatively fertile, moderate to low in organic matter, and susceptible to wind and water erosion. In poorly drained areas, soils are subject to salinization.

The plants and animals of the Great Plains vary along both the east-west and north-south gradients of precipitation and temperature. In the east, most of the region was originally covered by lush, tall grass, characterized by deep roots and vigorous growth. In the western part, where precipitation is lower, short grasses dominate. The short grasses form a dense sod, and their roots do not penetrate the soil deeply. Herbs also grow in the short grass region. Between the tall grass and short grass regions is a mixed area, composed of midgrasses and short grasses. Both kinds of grasses are intermixed and occur equally—mid-grasses form the upper layer of vegetation, and short grasses and sedges form the lower one. Woody vegetation in the grassland region occurs rarely under natural conditions, except in low areas and along rivers and streams. Pronghorn antelope, mule and white-tailed deer, jackrabbits, and other rodents are common throughout the region. Across the southern part of the Great Plains, grasses are mixed with shrubs and low trees. The northern boundary of these brushlands coincides with the northern distribution of sevral mammals—e.g., the Mexican ground squirrel and the gray fox.

The Interior Basin

The Interior Basin extends almost to the Canadian border in the north and to Arizona and New Mexico in the south. On the east, the region is bounded by the Rockies; the western and northern border is formed by the Cascade and Sierra Nevada Mountains. Relatively high elevations and level land surfaces characterize the area, but some regions are dissected by rivers or interrupted by small mountain chains. Some of the area consists of separate interior basins without drainage to the sea.

A variety of weather patterns occurs within the Interior Basin because of differences in topography, latitude, and elevation. The region is characterized by low and erratic precipitation. Average annual precipitation ranges from 0 to 48 inches at the tops of mountains. Most of the moisture comes as snow in the winter months.

Temperatures in the Interior Basin are like those of other continental climates. Both daily and seasonal temperatures range widely and reach extreme highs and lows. In the north, average monthly temperatures for January and July are 30° and 60° F. To the south, average temperatures are 35° and 80° F. Subzero winter temperatures in the mountains and summer temperatures over 100° F in southern valleys are common. The frost-free period varies from less than 60 days in high mountain valleys to over 200 days in southern lowland valleys.

Like the Great Plains, the northern part of the Interior Basin experiences strong winds in the winter and early spring as storms move across the area. Winds in the southern region tend to be from the south, and wind speeds are usually light to moderate.

Soils of the northernmost part of the Interior Basin developed in thick wind-blown deposits, sometimes mixed with volcanic ash. These soils are generally deep, fertile, and fine-textured, but prone to severe water erosion. Over much of the rest of the region, soils formed in residual materials. Salt flats and playas (the level floors of undrained basins that, at times, may become shallow lakes) are extensive in some areas and contain thick accumulations of alkaline and saline salts.

Vegetation in the region varies widely. In general, the broad valleys in the lower portion of the basin are covered by low shrubs. Almost pure stands of some shrubs occur, and many of them tolerate high alkali and salt concentrations in the soil. The lower elevations of the mountains and foothills in the area are usually covered by big sagebrush and grass, or by a combination of various low, shrubby, woody species. The mountains of the area support complex vegetation with a number of different plant communities, varying from low shrubs in the foothills, to trees at higher elevations, and grasses above timberline.

For the most part, the animals in this region are similar to those found in other areas. Wildlife species are especially important because of the wilderness character of the region. The area is also an important breeding and resting ground for migrating birds.

The Central Valley of California

To the west and south of the Sierra Nevada and Cascade mountain ranges and east of the Coast range is the Central Valley of California. The Central Valley constitutes two major river basins, that of the Sacramento River on the north and the San Joaquin River on the south. These two rivers flow toward each other and join in the Sacramento-San Joaquin delta. The combined basins extend nearly 500 miles in a northwest-southeast direction and average about 120 miles in width. They include more than one-third of California.

Generally, the climate of the Central Valley is mild. Most precipitation occurs in the fall and winter. Annual amounts tend to be higher in the north than in the south and range from 22 inches in the northern Sacramento Valley to 6 inches in the southern San Joaquin Valley.

Precipitation and resulting runoff vary not only from winter to summer of each year, but also in total annual amount in different years. For example, in extremely dry years, the runoff may be as little as one-third to one-tenth the average annual runoff. In extremely wet years, extensive flooding may be caused by runoff which may be two to over three times the average. Moreover, a succession of dry or wet years often occurs.

Temperatures in the Central Valley increase from north to south. Summers are hot and winters are mild. The average temperature for January is 45° F and the average for July is 70° F. The frost-free period ranges from 260 to 300 days.

Soils of the Central Valley formed on a variety of parent material, and properties vary. Generally, however, the soils developed on fertile alluvial deposits and are deep and fine-textured. In low areas, drainage may be poor and alkaline and saline salts may accumulate.

Evidence indicates that the Central Valley of California was once dominated by annual grasses. Today, many of these grasses have been eliminated by cultivation, fire, and grazing. Similarly, some animals such as the tule elk, pronghorn antelope, and feral horse and pig have disappeared from the valley and are confined to higher elevations. Now, deer, rabbits and other rodents, quail, wild turkeys, and partridges are common.

The Southwest

The Southwest includes areas in southern California, southern Nevada, southwest Utah, Arizona, southern New Mexico, and southwest Texas. The region is characterized by a broad spectrum of landscapes, including mountains, valleys, plains, and canyons.

The climate of the Southwest is arid, with hot summers and mild winters. Annual amounts of precipitation range from 0 inches to less than 16 inches. Most occurs during the summer months. Average temperatures range from 45° F in January to 85° F in July. Summer temperatures exceeding 100° F occur frequently. The frost-free period varies from 210 to 365 days in the southernmost part of the region.

Soils in the Southwest are variable. Generally, they formed in residual material and tend to be shallow and coarse in texture, although some are fine-textured and well-developed. In some areas, gravel and bare rock appear on the surface because intense desert storms remove soil accumulations. Salt flats and playas occur in low depressions with no exterior drainage.

Two large deserts occupy much of the area. The deserts of California and Arizona are characterized by large treeform cacti and numerous woody shrubs. These plants provide little groundcover, and small annual plants carpet the ground only after rare and heavy rainstorms. Although large animals are almost absent, small nocturnal burrowers such as rats and mice are common. To the east, the deserts of New Mexico and Texas are characterized by thorny scrub vegetation in open stands or thickets. Short grasses provide forage for pronghorn antelope, deer, and numerous rodents.

Cash Receipts From Farm Marketings, 17 Western States, 1980*

	Agricultural product (million dollars)		
State	*Livestock and products*	*Crops*	*Total*
Great Plains:			
Texas	5,920	4,114	10,034
Nebraska	3,873	2,569	6,442
Kansas	3,355	2,586	5,941
Oklahoma	1,986	1,148	3,134
South Dakota	1,710	723	2,433
North Dakota	662	1,656	2,318
Mountain region:			
Colorado	2,499	927	3,376
Idaho	907	1,085	1,992
Arizona	864	1,036	1,900
Montana	727	651	1,378
New Mexico	850	273	1,123
Wyoming	572	110	682
Utah	376	124	500
Nevada	150	65	215
Pacific region:			
California	4,452	9,210	13,662
Washington	807	1,807	2,614
Oregon	621	973	1,594
Total, 17 Western States	30,281	29,058	59,339
Total, United States	69,209	68,806	138,015

*Other income derived from farming (e.g., Government payments and nonmoney income) are not included in totals.

SOURCE: U.S. Department of Agriculture, Economics and Statistics Service, *Agricultural Outlook*, March 1981, AO-63, p. 25.

Agricultural Exports in the 17 Western States, by State, October-September, 1979-80 and 1980-81

State	Total agricultural exports (million dollars)	Leading exports*
Great Plains:		
Texas:		Cotton, feed grain wheat, rice, animals, and meat
1980	2,976	
1981	2,577	
Kansas:		Wheat, feed grains, soybeans, animals and meat, fats and oils
1980	2,085	
1981	2,263	
Nebraska:		Feed grains, wheat, soybeans, animals and meat, fats and oils
1980	1,873	
1981	2,114	
North Dakota		Wheat, sunflower seeds and oil, feed grains, seeds, feed and fodder
1980	1,435	
1981	1,144	
Oklahoma:		Wheat, cotton, animals and meat, fats and oils, hides and skins
1980	1,003	
1981	931	
South Dakota:		Wheat, feed grains, soybeans, sunflower seeds and oil
1980	697	
1981	708	
Mountain region:		
Colorado:		Wheat, feed grains, animals and meat, seeds, hides and skins, vegetables
1980	534	
1981	780	
Idaho:		Wheat, vegetables, feed grains, seeds, hides and skins
1980	467	
1981	634	
Montana:		Wheat, feed grains, animals and meat, fats and oils
1980	474	
1981	513	
Arizona		Cotton, wheat, fruits, cottonseed, animals and meat
1980	439	
1981	488	
New Mexico:		Wheat, feed grains cotton, animals and meat, fats and oils
1980	139	
1981	151	
Utah:		Hides and skins, wheat, animals and meats, feed grains
1980	104	
1981	114	
Wyoming:		Wheat, animals and meat, hides and skins, fats and oils
1980	76	
1981	94	
Nevada:		Animals and meat, hides and skins, fats and oils
1980	23	
1981	25	
Pacific region:		
California:		Fruits, nuts, cotton vegetables, wheat
1980	3,253	
1981	3,589	
Washington:		Wheat, vegetables, fruits, seeds, hides and skins
1980	699	
1981	1,018	
Oregon:		Wheat, vegetables, seeds, hides and skins, animals and meat
1980	385	
1981	513	
Total, 17 Western States:		
1980	16,662	
1981	17,656	
Total, United States:		
1980	40,481	
1981	43,789	
17 Western States, percent of total U.S.:		
1980	41	
1981	40	

*Exports are arranged in approximate, decreasing order of monetary value.

SOURCE: USDA, Economic Research Service, *Foreign Agricultural Trade of the United States*, March/April 1982, table 17.

Appendix A References

1. Bailey, R. G., *Description of the Ecoregions of the United States*, U.S. Department of Agriculture, Miscellaneous Publication No. 1391, 1980.
2. Brengle, K. G., *Principles and Practices of Dryland Farming* (Boulder, Colo.: Colorado Associated University Press, 1982).
3. Ferguson, Hayden, Lyle, William, Fenster, Charles, and Wendt, Charles, "Dryland Agriculture," OTA, unpublished draft report, August 1982.

Appendix B

Western Regional Water Characteristics

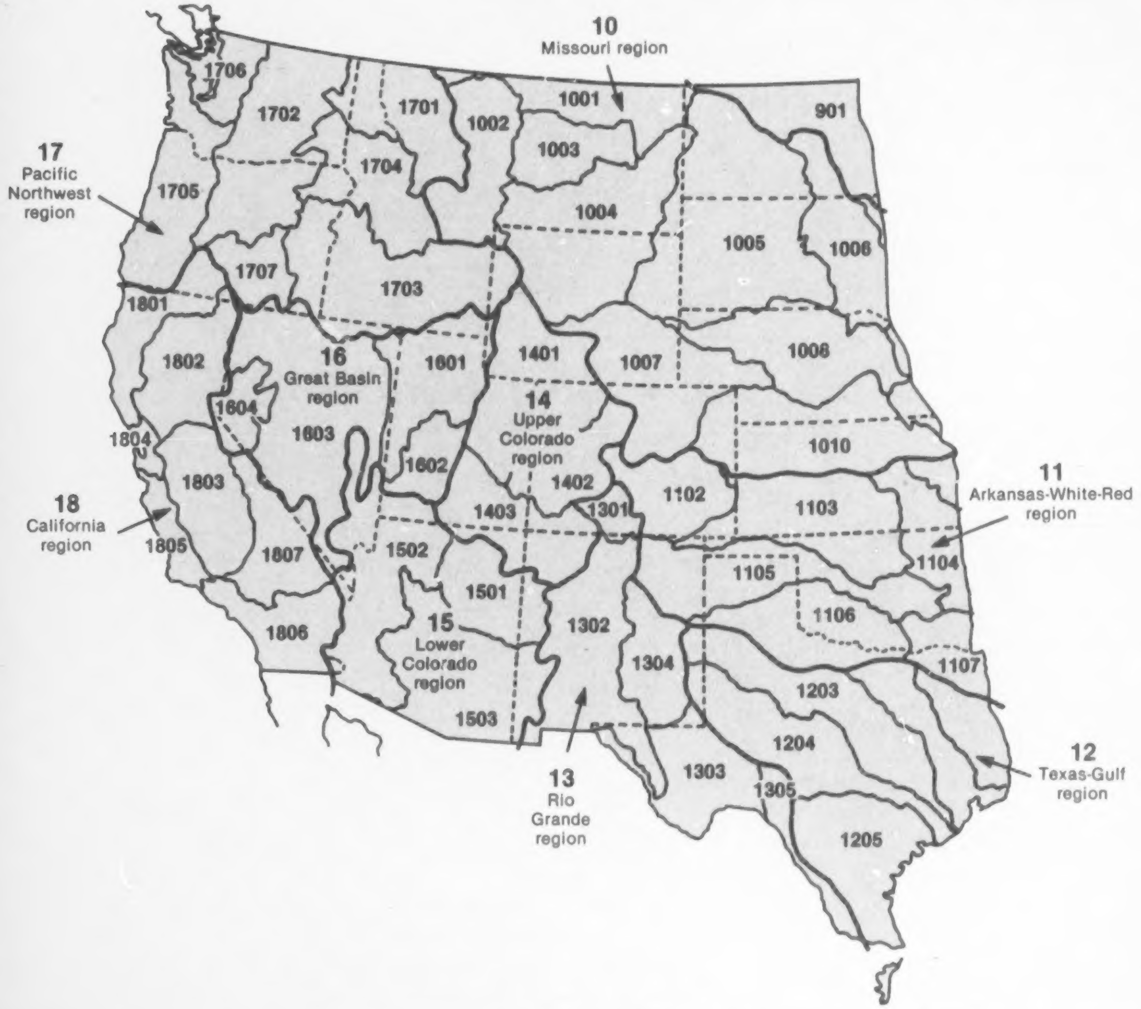
NOTE: **This appendix presents in more detail the data on which chapters III and X have been based.** The data are presented primarily in graphical and tabular form, designed generally to supplement the discussion of the water supply/use relationships of the Western United States with specific data or discussions related to each of the surface- and ground-water resource regions of the area. The main source for the surface water section of this appendix is the Second National Water Assessment (5). One of the primary difficulties in assessing a water-related problem in the Western United States today lies in the often incompatible data bases used to describe water supply/demand relationships in the region. Where such discrepancies are noted in this appendix, the reader is referred to the original publications from which the data were obtained.

The Water Resources Regions of the Western United States With Water Supply/Use Patterns for Selected Subregions

The fundamental hydrologic unit is the river basin. The United States was subdivided into 21 major water geographic units based on river basins in 1970 by the U.S. Water Resources Council. Hydrologic data are collected and organized according to these units, which are: 1) regions, 2) subregions, 3) accounting units, and 4) cataloging units. These hydrologic areas contain either the drainage area of a major river, such as the Missouri region, or the combined drainage areas of a series of rivers, such as the Texas-Gulf region. The second level of classification, the subregion, contains either an area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin, or a group of streams forming a coastal drainage area. All subregional boundaries are hydrologic except where discontinued at international boundaries. For the purposes of this discussion, only the region and subregion categories will be used. The subregion classification is that used in the Second National Water Assessment (5). This differs somewhat from the accounting units of the USGS which are also hydrologically defined.

The 17 Western States have been divided into nine water resources regions, containing 52 subregions (fig. B-1). There are wide variations among these water resources regions in the spatial and temporal availability of water and in the uses of that water (figs. B-2,B-3,B-4,B-5).

Figure B-1.—Water Resources Regions and Subregions of the Arid and Semiarid Portions of the United States

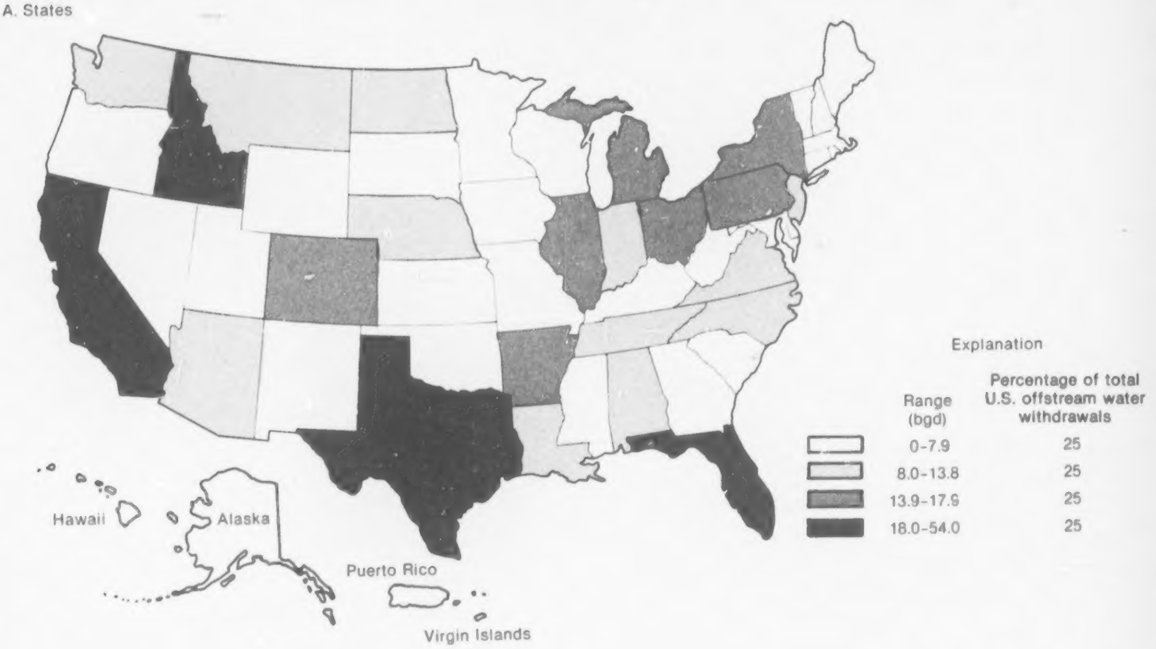

10
Missouri region
1706
1702
1701
1002
1001
901
17
Pacific
Northwest
region
1704
1003
1705
1004
1005
1006
1707
1703
1801
1008
16
Great Basin
region
1802
1601
1401
1007
14
Upper
Colorado
region
1604
1603
1804
1010
1602
1402
1102
11
Arkansas-White-Red
region
18
California
region
1803
1403
1301
1103
1805
1807
1502
1105
1104
1501
15
Lower
Colorado
region
1106
1806
1302
1304
1107
1503
1203
12
Texas-Gulf
region
13
Rio
Grande
region
1204
1303
1305
1205

These are the subdivisions used by WRC in the Second National Water Assessment. The subregions do not correspond to those used by USGS.

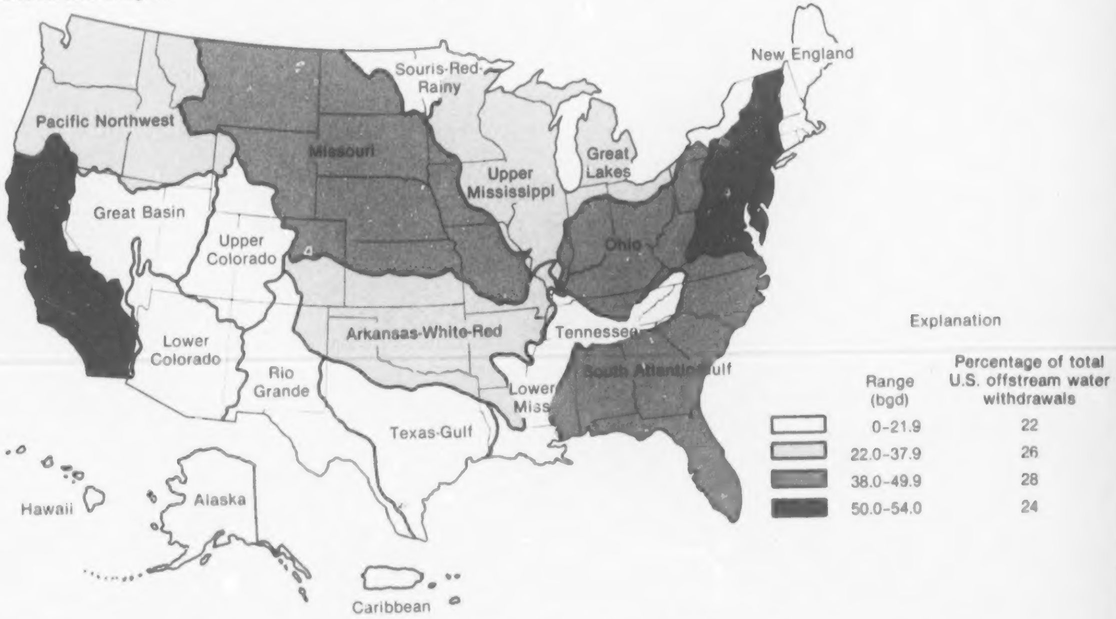
SOURCE: U.S. Water Resources Council, *The Nation's Water Resources 1975-2000* (Washington, D.C.: U.S. Government Printing Office, 1978).

Figure B-2.—Total Offstream Water Withdrawals by States and Water Resources Regions, 1980

A. States

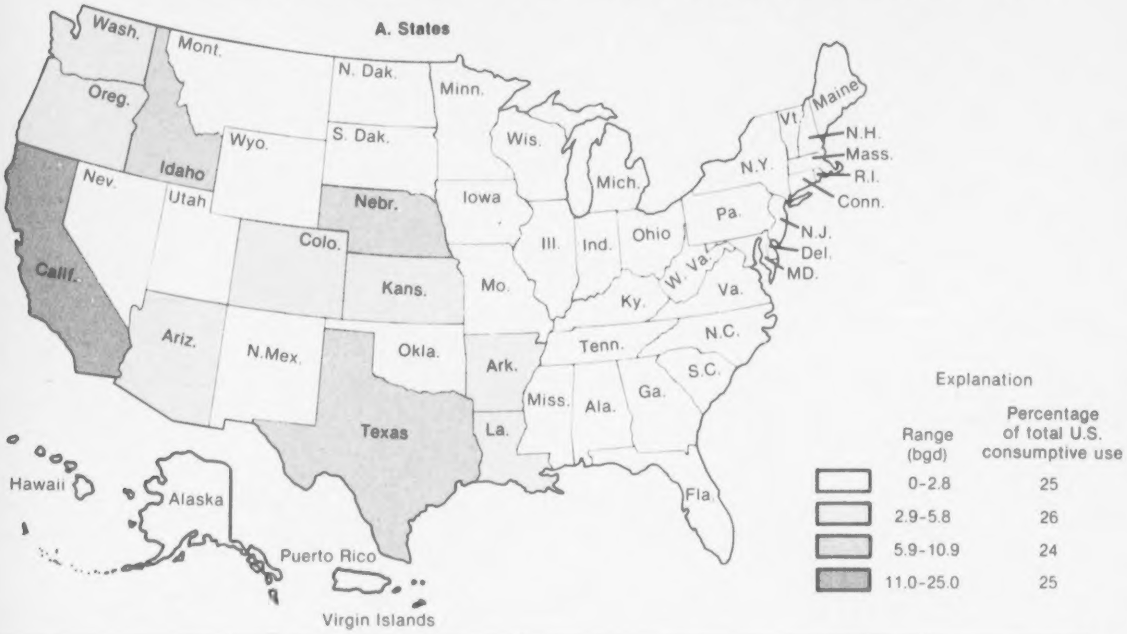

Hawaii
Alaska
Puerto Rico
Virgin Islands
Explanation
Range (bgd)
Percentage of total U.S. offstream water withdrawals
0-7.9 25
8.0-13.8 25
13.9-17.9 25
18.0-54.0 25

B. Water-resources regions


New England
Souris-Red-Rainy
Pacific Northwest
Missouri
Upper Mississippi
Great Lakes
Great Basin
Upper Colorado
Ohio
Arkansas-White-Red
Tennessee
Lower Colorado
Rio Grande
Lower Miss
South Atlantic-Gulf
Texas-Gulf
Hawaii
Alaska
Caribbean
Explanation
Range (bgd)
Percentage of total U.S. offstream water withdrawals
0-21.9 22
22.0-37.9 26
38.0-49.9 28
50.0-54.0 24

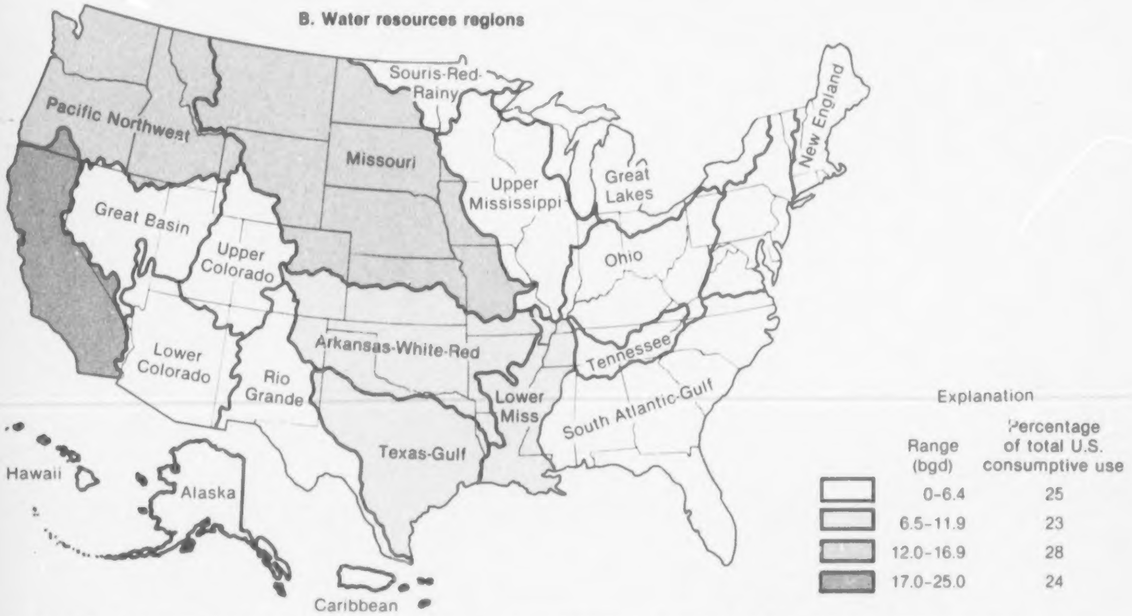
SOURCE: W. Solley, E. Chase, and W. Mann IV, *Estimated Use of Water in the United States in 1980*, U.S. Geological Survey Circular 1001, 1983.

Figure B-3.—Freshwater Consumptive Use, by State and Water Resources Regions, 1980



A. States

Wash.
Mont.
N. Dak.
Minn.
Oreg.
Idaho
Wyo.
S. Dak.
Wis.
Mich.
N.Y.
Vt.
Maine
N.H.
Mass.
R.I.
Conn.
Nev.
Utah
Nebr.
Iowa
Pa.
N.J.
Del.
MD.
Colo.
Ill.
Ind.
Ohio
W. Va.
Va.
Calif.
Kans.
Mo.
Ky.
N.C.
Tenn.
Ariz.
N.Mex.
Okla.
Ark.
S.C.
Miss.
Ala.
Ga.
Texas
La.
Fla.
Hawaii
Alaska
Puerto Rico
Virgin Islands
Explanation
Range (bgd)
Percentage of total U.S. consumptive use
0-2.8 25
2.9-5.8 26
5.9-10.9 24
11.0-25.0 25



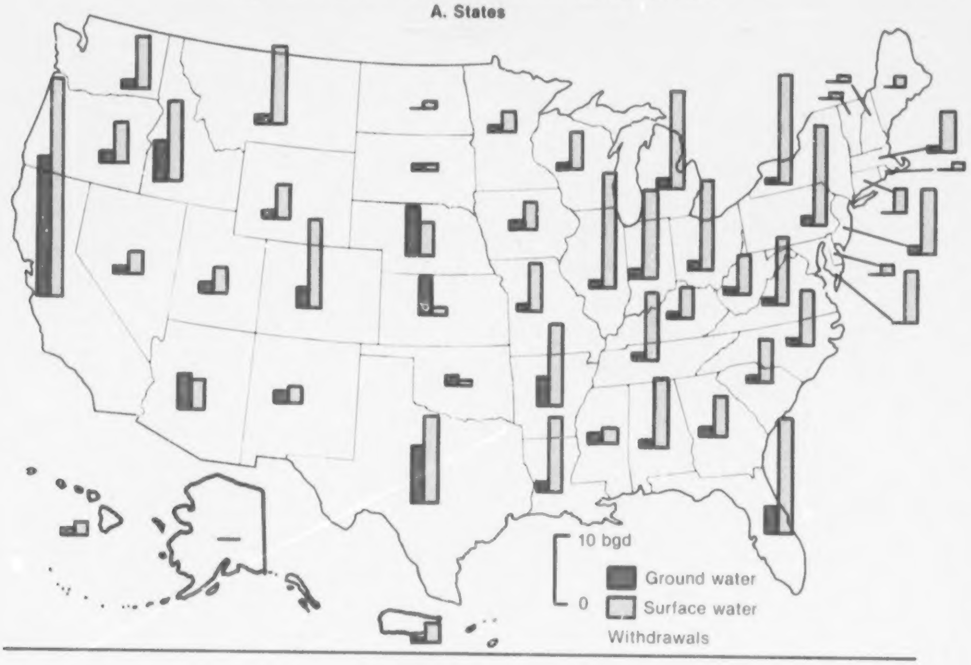
B. Water resources regions

Souris-Red-Rainy
New England
Pacific Northwest
Missouri
Upper Mississippi
Great Lakes
Great Basin
Upper Colorado
Ohio
Arkansas-White-Red
Tennessee
Lower Colorado
Rio Grande
Lower Miss
South Atlantic-Gulf
Texas-Gulf
Hawaii
Alaska
Caribbean
Explanation
Range (bgd)
Percentage of total U.S. consumptive use
0-6.4 25
6.5-11.9 23
12.0-16.9 28
17.0-25.0 24

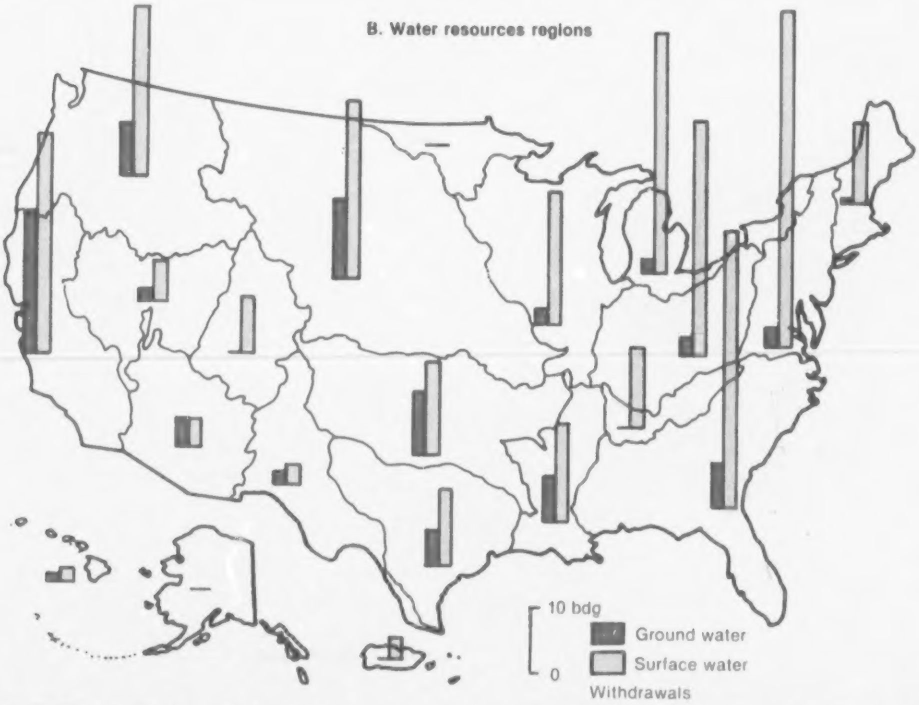
SOURCE: W. Solley, E. Chase, and W. Mann IV, *Estimated Use of Water in the United States in 1980,* U.S. Geological Survey Circular 1001, 1983.

Figure B-4.—Withdrawals for Offstream Use From Ground and Surface Water Sources, by States and Water Resources Regions, 1980

A. States


10 bgd
0
Ground water
Surface water
Withdrawals

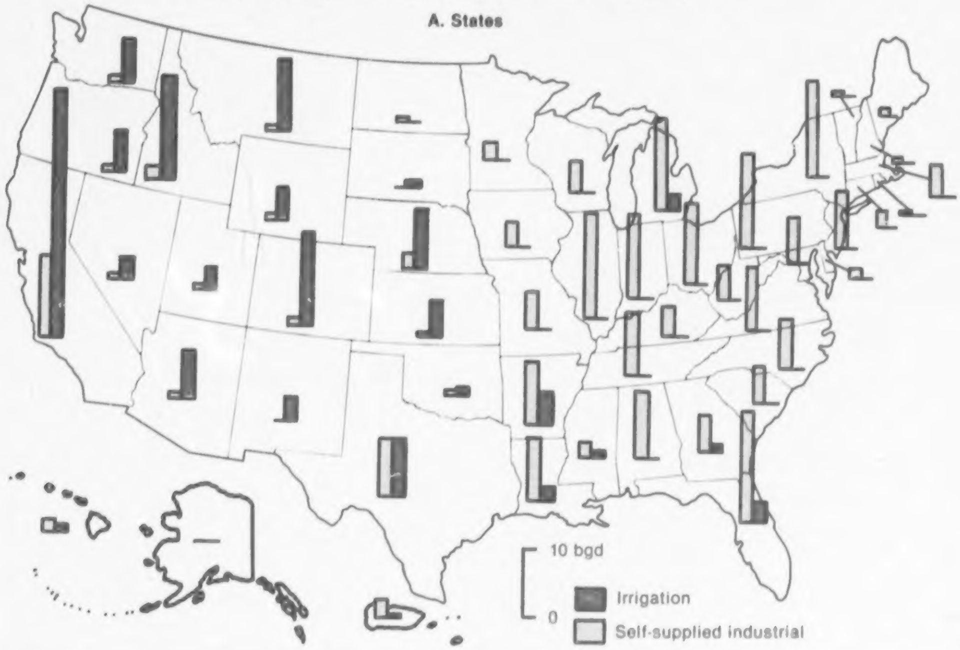
B. Water resources regions


10 bdg
0
Ground water
Surface water
Withdrawals

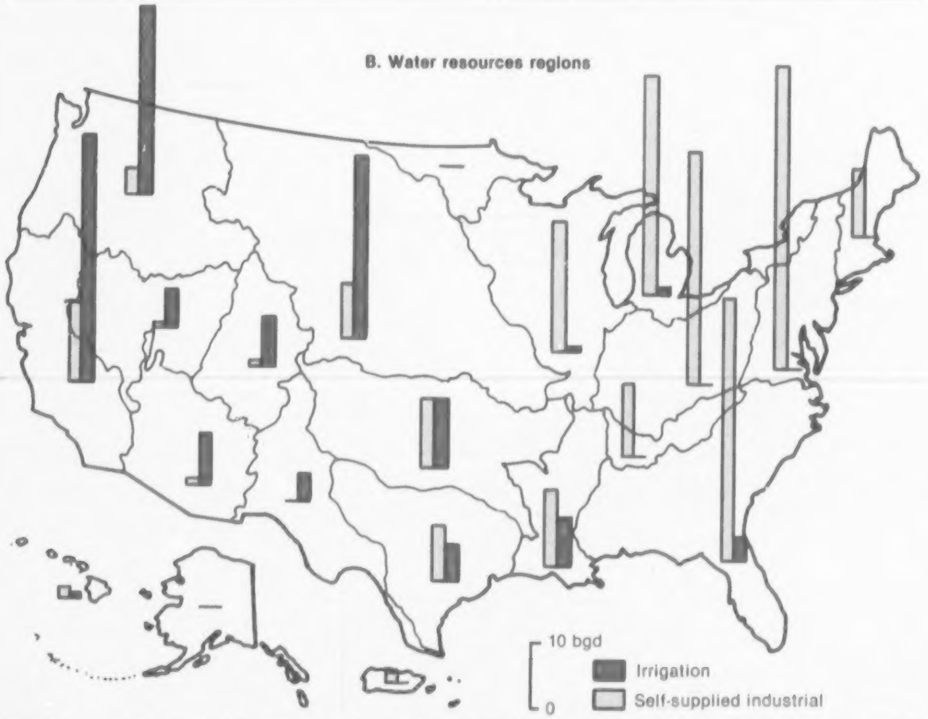
SOURCE: W. Solley, E. Chase, and W. Mann IV, *Estimated Use of Water in the United States in 1980*, U.S. Geological Survey Circular 1001, 1983.

Figure B-5.—Comparison of Withdrawals for Self-Supplied Industrial Use and Irrigation Use, by States and Water Resources Regions, 1980

A. States


10 bgd
0
Irrigation
Self-supplied industrial

B. Water resources regions


10 bgd
0
Irrigation
Self-supplied industrial

SOURCE: W. Solley, E. Chase, and W. Mann IV, *Estimated Use of Water in the United States in 1980*, U.S. Geological Survey Circular 1001, 1983.

Water-Region Maps

The Missouri River Basin: Water Resources Region 10

The Missouri River Basin—including portions of Montana, Wyoming, Colorado, North and South Dakota, Nebraska, and Kansas—contains one-sixth the land area of the 48 contiguous States, about 511,309 square miles (mi^2). Estimates of annual runoff range from 49.4 million acre-feet (maf) (5) to 60.5 maf (4). There are six large constructed reservoirs on the Missouri mainstem and these, together with tributary reservoirs, have a normal storage capacity of slightly more than 83 maf. This storage capacity is approximately 1.7 times the mean annual flow. Total withdrawals of water for all uses is approximately 43 maf, one-half of normal storage. Withdrawals for irrigation are slightly more than 35 maf, or 81 percent of all withdrawals. Forty-one percent of all water withdrawn is consumed, the majority for irrigated agriculture.

The relationship between water availability and water use varies greatly within this region. As can be seen in figure B-6, in general there is a surplus of water over demand in the northern States of Montana and North and South Dakota, while the southern States in the basin—Colorado, Nebraska, and Kansas—use all of the available surface water and make up the deficit between supply and use by extracting water from ground water aquifers during the period of deficit. The extent to which current levels of water use can be sustained will largely be determined by the availability of ground water reserves. Without some shift in water use patterns, it is apparent that existing surface water resources are totally committed in the southern portion of the basin.

Water Resources Region 10: Missouri River

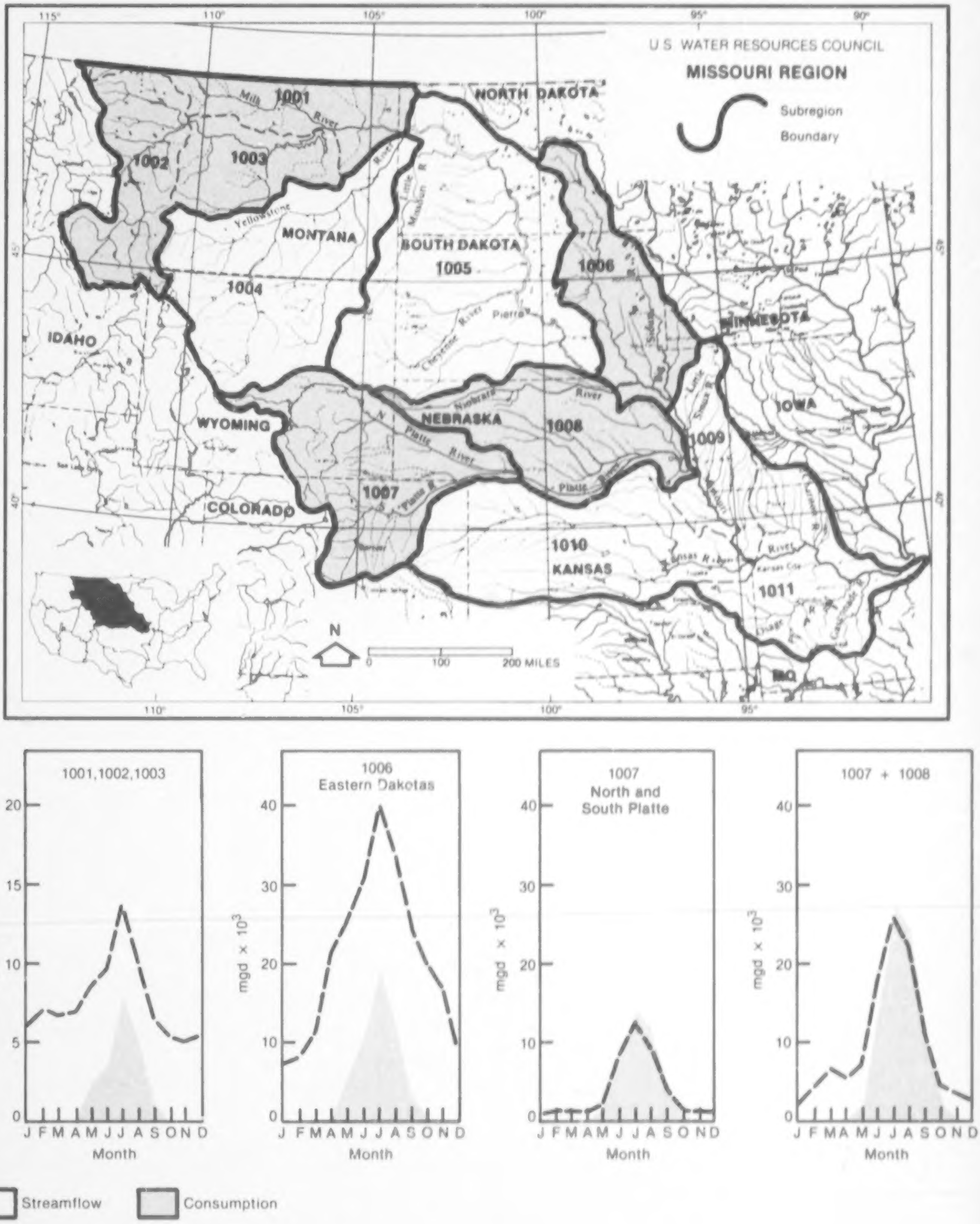
The relationship between water supply and use by month for selected subregions of the Missouri River Basin. While there is an excess of supply over demand during all months in the northern sections of this basin, most subregions in the southern parts experience a water supply shortage during the summer months when use is at the annual maximum.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals		Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
			Total (mgd)	Overdraft (mgd)				
1001	5,910	134	22	1	82	923	318	23%
1002	4,770	1,373	59	0	230	4,376	1,315	22
1003	5,530	5,081	11	1	545	335	150	21
1004	7,760	1,017	165	7	203	7,306	2,086	21
1005	14,200	14,415	179	10	2,186	1,145	512	24
1006	16,500	191	177	13	134	244	180	22
1007	1,020	2,474	1,849	435	366	8,825	3,314	85
1008	3,920	153	2,996	450	134	5,477	3,346	69
1009	24,800	36	288	30	12	2,084	186	32
1010	3,910	931	4,432	1,600	842	5,808	3,866	63
1011	44,100	1,536	229	10	190	1,493	196	27
Total region ..	44,100	27,161	10,407	2,557	4,924	38,016	15,469	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-6.—The Missouri Water Resources Region


115°
110°
105°
100°
95°
90°
45°
40°
U.S. WATER RESOURCES COUNCIL
MISSOURI REGION
Subregion
Boundary
1001
1002
1003
1004
1005
1006
1007
1008
1009
1010
1011
NORTH DAKOTA
MONTANA
SOUTH DAKOTA
IDAHO
WYOMING
NEBRASKA
COLORADO
KANSAS
MINNESOTA
IOWA
MO
Milk River
Yellowstone
Little Missouri R
River
Pierre
Cheyenne River
Niobrara River
N Platte River
Platte R
Platte River
Kansas River
Kansas City
Osage R
Big Sioux R
N
0
100
200 MILES
1001,1002,1003
1006
Eastern Dakotas
1007
North and
South Platte
1007 + 1008
mgd × 10³
0
5
10
15
20
30
40
J F M A M J J A S O N D
Month
Streamflow
Consumption

The Arkansas, White, and Red River Basins: Water Resources Region 11

The Arkansas-White-Red region covers about 244,000 mi², 7 percent of the Nation. It lies in the south-central portion of the United States between the Continental Divide and the Mississippi River. Three major rivers—the Arkansas, White, and Red—drain the region, which includes all of Oklahoma and parts of Colorado, New Mexico, Kansas, Missouri, Arkansas, Texas, and Louisiana. It has been included in the present assessment because much of the basin lies in the southern Great Plains region of the Western United States.

The total surface flow from the region in an average year is estimated at 70.1 maf (5) and 81.8 maf (4). Normal storage in reservoirs in the region is 30.3 maf, or approximately 45 percent of the mean annual streamflow of the region. Total withdrawals for all uses in 1975 were 14.4 maf, of which 11.2 maf, or 78 percent, were withdrawn for irrigation. Sixty-three percent of all water withdrawn is consumed, the majority (88 percent) by irrigated agriculture.

Water supply and use relationships, which are illustrated graphically for various selected subregions within the basin in figure B-7, vary widely, both spatially and temporally, throughout this basin. Headwaters subregions, as represented by 1102, the upper Arkansas River, have a high apparent excess of supply. The intermediate reaches of the Arkansas and Red Rivers, in portions of Kansas, Oklahoma, and Texas, experience periods of 2 months (July-August) when demands made on the surface water resources exceed the supply, while in the lower reaches of these same rivers, in eastern Oklahoma and Texas, supply generally exceeds use. The deficit in supply in the middle reaches of the Arkansas and Red Rivers has been met by overdrafting the Ogallala aquifer, which is now showing signs of depletion in portions of this area. Here, water-use patterns and trends will have to be modified if a balance between available water supplies and water uses is to be achieved.

Water Resources Region 11: Arkansas-White-Red Rivers

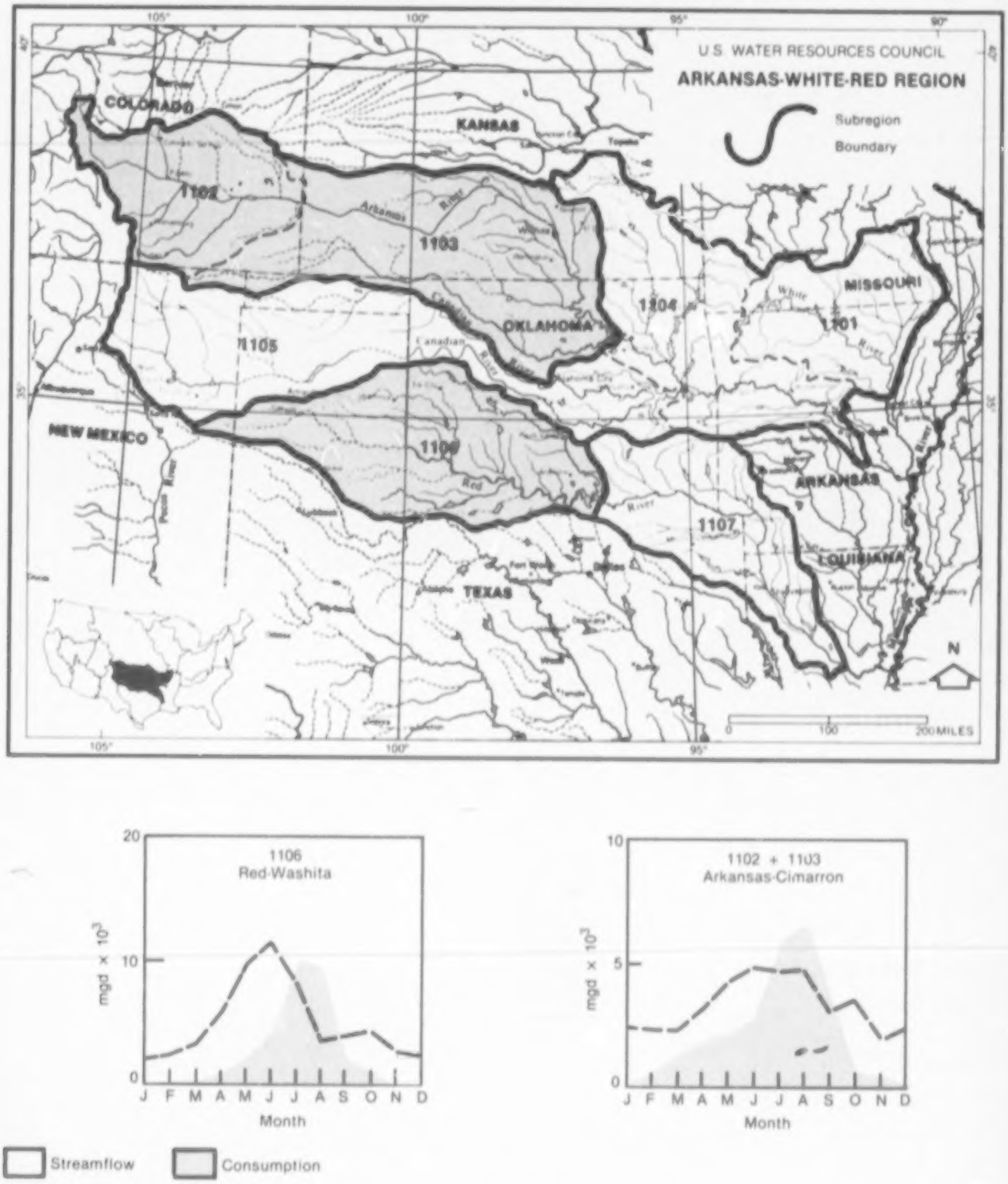
Water supply and use for the Arkansas-White-Red water resources region. Natural supply exceeds the demand during the winter months in the region as a whole. However, during the summer months when agricultural use is at its peak, water use either exceeds supply or approaches it very closely in most subregions.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals		Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
			Total (mgd)	Overdraft (mgd)				
1001	15,900	3,477	301	2	0	196	96	1%
1002	155	416	217	21	126	1,800	743	85
1003	4,280	198	3,619	2,098	547	3,456	2,031	56
1004	27,000	2,107	150	6	203	1,024	299	19
1005	3,540	1,466	2,805	2,069	659	3,168	2,440	62
1006	2,320	1,473	1,647	1,259	1,007	2,746	2,276	68
1007	1,970	736	107	2	73	478	179	12
Total region ..	62,600	9,853	8,846	5,457	2,615	12,868	8,064	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-7.—The Arkansas-White-Red Water Resources Region


U.S. WATER RESOURCES COUNCIL
ARKANSAS-WHITE-RED REGION
Subregion Boundary
105°
100°
95°
90°
40°
35°
COLORADO
KANSAS
MISSOURI
OKLAHOMA
NEW MEXICO
TEXAS
ARKANSAS
LOUISIANA
1101
1102
1103
1104
1105
1106
1107
Arkansas River
Canadian River
White River
Red River
Pecos River
N
0
100
200 MILES
1106
Red-Washita
mgd × 10³
0
10
20
J F M A M J J A S O N D
Month
1102 + 1103
Arkansas-Cimarron
mgd × 10³
0
5
10
J F M A M J J A S O N D
Month
Streamflow
Consumption

SOURCE: Second National Water Assessment.

The Texas-Gulf Basins: Water Resources Region 12

The Texas-Gulf region extends from the Gulf of Mexico northwest for some 650 miles into the southern Great Plains. Almost all of the region (94 percent) lies within the State of Texas, although small portions of Louisiana (1 percent) and New Mexico (5 percent) are included. The total surface area of the region is about 177,700 mi^2, approximately 5 percent of the total surface area of the Nation. The region consists of the drainage areas of the Sabine, Neches, Trinity, San Jacinto Brazos, Colorado, Lavaca, Guadalupe, San Antonio, and Nueces Rivers. These rivers drain in a general southeasterly course to the Gulf of Mexico. The total streamflow from the region during an average year is estimated to be 31.7 maf (5) and 35.8 maf (4). Streamflow has been as low as 12.7 maf during dry years. Normal storage in the basin is 23.5 maf, or 74 percent of the mean annual streamflow. Total withdrawals in the region are 19 maf annually, of which 8.1, or 43 percent, are from ground water. Sixty-eight percent of the total withdrawals were for irrigation. Of the total withdrawals, 12.6 maf were consumed, of which irrigation consumed 10.5, or 83 percent.

Streamflow volumes decrease from east to west across the region, while considerable irrigated agriculture is practiced in both the northern and western portions of the basin. This creates an imbalance between supply and use curves, which is illustrated graphically in figure B-8 for the two central subregions, the Brazos (1203) and Colorado (1204). It can be seen that in both these subregions, use exceeds surface supply during all or much of the months of June, July, August, and September. This excess demand has been met in the past by overdrafting portions of the Ogallala and Edwards-Trinity aquifers, which underlie the extreme western boundary of the region. At least in the case of the Ogallala aquifer, local depletions are occurring and can be expected to grow as declining water tables and rising energy costs further restrict the use of this water source.

Water Resources Region 12: Texas-Gulf Region

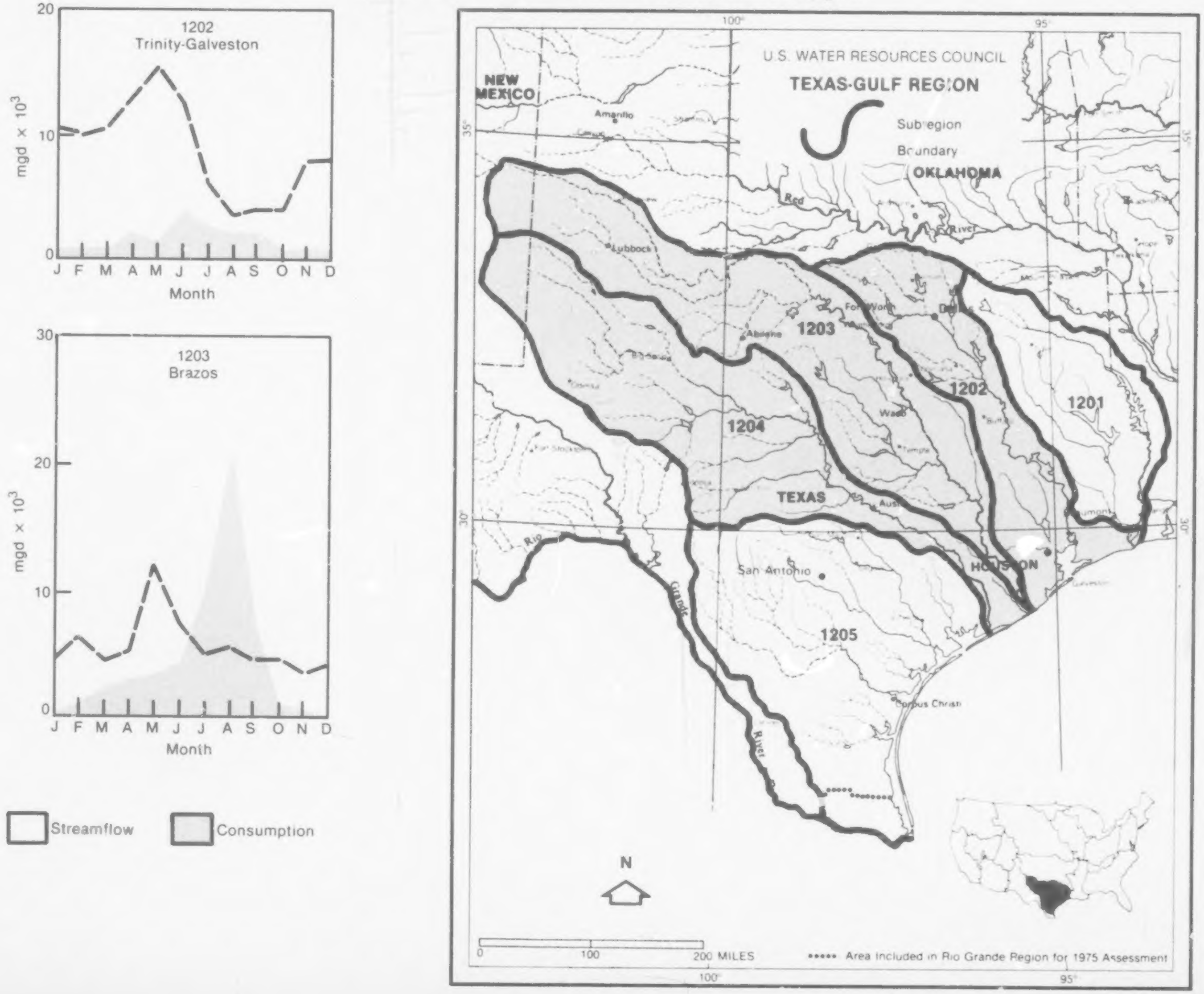
In the central portion of the Texas-Gulf region, the use of water exceeds the supply during all summer months. An east-west gradient of water availability exists such that the supply-use relationship becomes progressively poorer from the Sabine-Neches subregion in the east to the Nueces subregion in the southwestern portion of the State of Texas.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals		Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
			Total (mgd)	Overdraft (mgd)				
1201	10,300	3,065	163	39	49	2,928	502	5%
1202	7,500	1,913	617	297	335	9,641	1,601	18
1203	1,810	1,262	1,215	1,157	473	4,758	3,061	84
1204	4,720	1,032	4,395	3,767	694	6,255	4,850	82
1205	3,940	387	832	318	154	2,508	1,245	26
Total region ..	28,270	7,660	7,222	5,578	1,705	26,088	11,259	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-8.—The Texas-Gulf Water Resources Region


1202
Trinity-Galveston
mgd × 10³
20
10
0
J F M A M J J A S O N D
Month
1203
Brazos
mgd × 10³
30
20
10
0
J F M A M J J A S O N D
Month
Streamflow
Consumption
U.S. WATER RESOURCES COUNCIL
TEXAS-GULF REGION
Subregion
Boundary
NEW MEXICO
OKLAHOMA
TEXAS
Amarillo
Lubbock
Abilene
Fort Worth
Dallas
Waco
Temple
Austin
San Antonio
Houston
Corpus Christi
Red River
Rio Grande River
1201
1202
1203
1204
1205
N
0
100
200 MILES
Area Included in Rio Grande Region for 1975 Assessment
100°
95°
35°
30°

The Rio Grande Basin: Water Resources Region 13

The Rio Grande originates on the eastern slopes of the Continental Divide in Colorado and flows south through New Mexico to enter Texas at El Paso. Along the Texas reach of the river, it forms the international boundary between the United States and Mexico. The total drainage area is 230,000 mi², of which 93,000 mi² are in Mexico and 137,000 mi² are in the United States. Forty-eight thousand square miles drain into closed basins. The principal tributaries of the Rio Grande and the Pecos River, draining portions of New Mexico and Texas, are the Rio Conchos in Mexico, the Rio Puerco in New Mexico, and the Rio Chama in New Mexico.

The streamflow in the Rio Grande basin is largely derived from melting snow in the mountains in the northern portion of the region. Because of historical patterns of water diversion for irrigated agriculture, which predate European settlement of the region and the initiation of systematic streamflow measurements, and because of contributions from the Mexican portion of the basin to total streamflow at the mouth of the river, water supply estimates based on total streamflow measurements are, in all probability, misleading. The mean annual flow of the Rio Grande originating within the United States portion of the basin is estimated to be 1.4 maf (5) or 5.6 maf (4). This fourfold difference in estimates of annual flow volumes make management decisions regarding the Rio Grande basin particularly difficult. The aggregate surface storage in the basin is estimated to be 7.8 maf.

Total withdrawals are estimated to be 7.1 maf, of which 6.4 maf, or 90 percent, are for irrigated agriculture. Total consumption is estimated to be 4.8 maf, of which 92 percent is used by irrigation. Ground water withdrawals are 2.6 maf/year, which is 37 percent of the total withdrawal.

While there is apparently a serious question concerning the accuracy of the supply data for the Rio Grande basin, some idea of the nature of the extent to which the water resources are being used can be obtained from an examination of figure B-9. This graphic comparison of supply and use relationships is for the upper Rio Grande and Pecos Rivers, where the ambiguities of the lower reaches are minimized to some extent. It can be seen that in both subregions (1303 and 1304) use slightly exceeds supply during most months of the year. The statement of the Second National Water Assessment that "there are no surplus flows to meet new demands or to expand existing uses" appears to be correct. Because it is also estimated that ground water withdrawals represent an overdrafting of the basin aquifers by as much as 700,000 acre-ft/yr, it would seem that a gradual reduction from current use levels is inevitable.

Water Resources Region 13: Rio Grande River

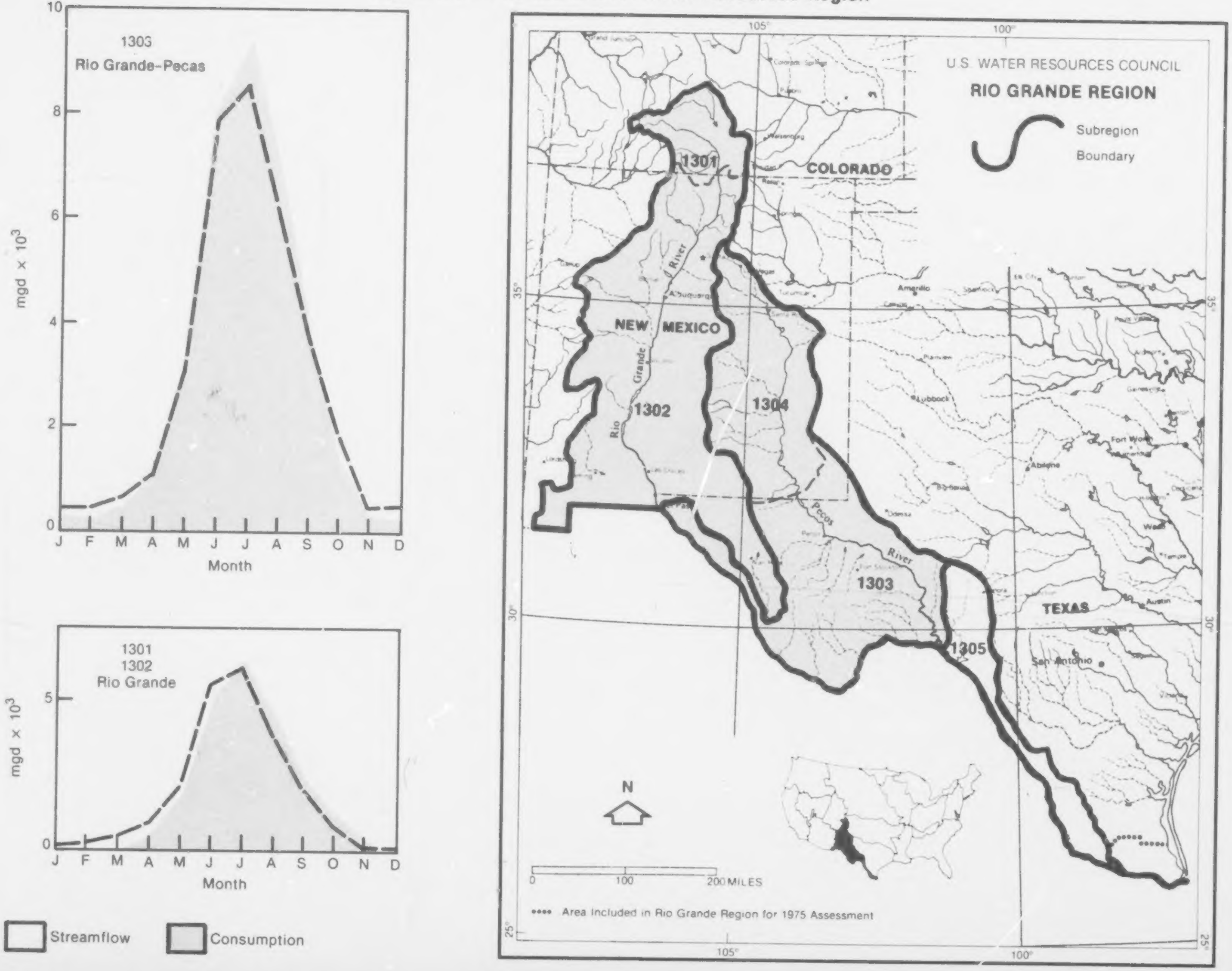
In this entire region, water use exceeds or equals supply during virtually all months of the year. Water supply in the lower Rio Grande is difficult to assess, owing to the ungaged contribution from Mexico. The available data suggest that there is little or no excess water in the lower reaches of the Rio Grande River.

			Ground water withdrawals					
Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Total (mgd)	Overdraft (mgd)	Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
1301	267	114	590	0	18	932	581	69%
1302	343	1,071	611	265	129	2,118	1,247	96
1303	582	108	679	290	73	873	630	102
1304	122	58	400	89	74	897	562	94
1305	1,230	1,183	55	13	436	1,501	1,220	88
Total region ..	1,230	2,534	2,335	657	730	6,321	4,240	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-9.—The Rio Grande Water Resources Region


1303
Rio Grande-Pecas
mgd × 10³
0
2
4
6
8
10
J F M A M J J A S O N D
Month
1301
1302
Rio Grande
mgd × 10³
0
5
J F M A M J J A S O N D
Month
Streamflow
Consumption
U.S. WATER RESOURCES COUNCIL
RIO GRANDE REGION
Subregion
Boundary
COLORADO
NEW MEXICO
TEXAS
1301
1302
1303
1304
1305
Rio Grande River
Pecos River
Albuquerque
Amarillo
Lubbock
Fort Worth
Abilene
Austin
San Antonio
105°
100°
35°
30°
25°
N
0
100
200 MILES
•••• Area Included in Rio Grande Region for 1975 Assessment

The Colorado River Basin: Water Resources Regions 14 and 15

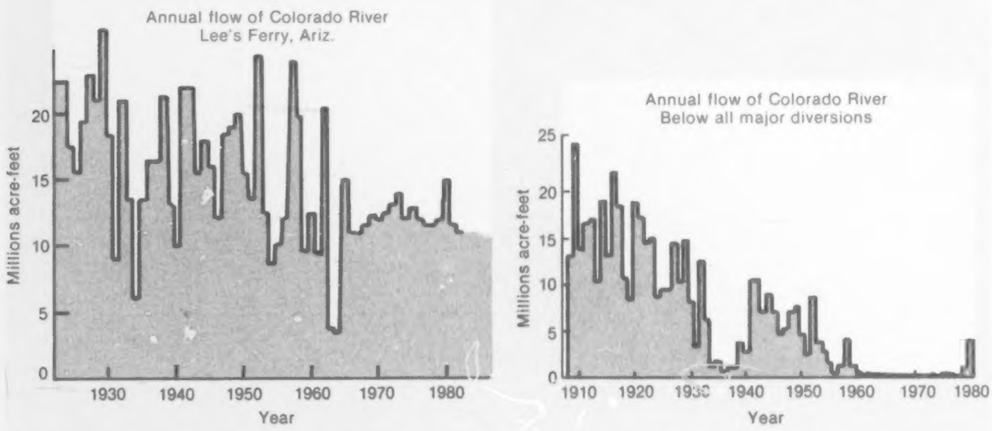
It has become customary in most discussions of regional water resources to divide the Colorado River Basin into an upper region (14) and a lower region (15) at Lee's Ferry, Ariz. This division is designed to reflect provisions of the Colorado River Compact but has limited hydrologic utility.

The Colorado River Basin has a total surface area of approximately 257,000 mi², of which slightly more than 100,000 mi² are in the upper basin. This basin lies immediately west of the Continental Divide and includes parts of Wyoming, Utah, Colorado. Arizona, New Mexico, and Nevada.

Estimates of mean annual streamflow for the entire Colorado River Basin vary from a low of 12.4 maf (5) to a high of 18.1 maf (4). Historically, the flow of the river has varied widely, and the value given for a mean annual discharge depends very much on the period of time represented by the data on which it is based. While this is equally true of virtually all rivers in the Western United States, which have a high variability from year to year, it is perhaps most interesting in terms of the Colorado River. Because the mean flow of the river has declined since the original division of the annual streamflow among the upper and lower basin States, it has become a well-known example of the need to understand fully, prior to any allocations, the regime of any hydrologic regime subject to political agreement (fig. B-10).

Figure B-10.—The Colorado River Basin Water Resources Region

The annual flow of the Colorado River at Lee's Ferry, Ariz., immediately downstream from Lake Powell (above) and at its outflow into the Gulf of California (below [illegible]e trend toward lower annual flow volumes in recent decades is largely confined to the lower Colorado, where a majority of the water diversions are located.



SOURCE: J. Bredehoeft, "Physical Limitations on Water Resources in the Arid West," paper presented at: *Impacts of Limited Water for Agriculture in the Arid West*, Asilomar, Calif., 1982.

Water Resources Region 14: Upper Colorado River

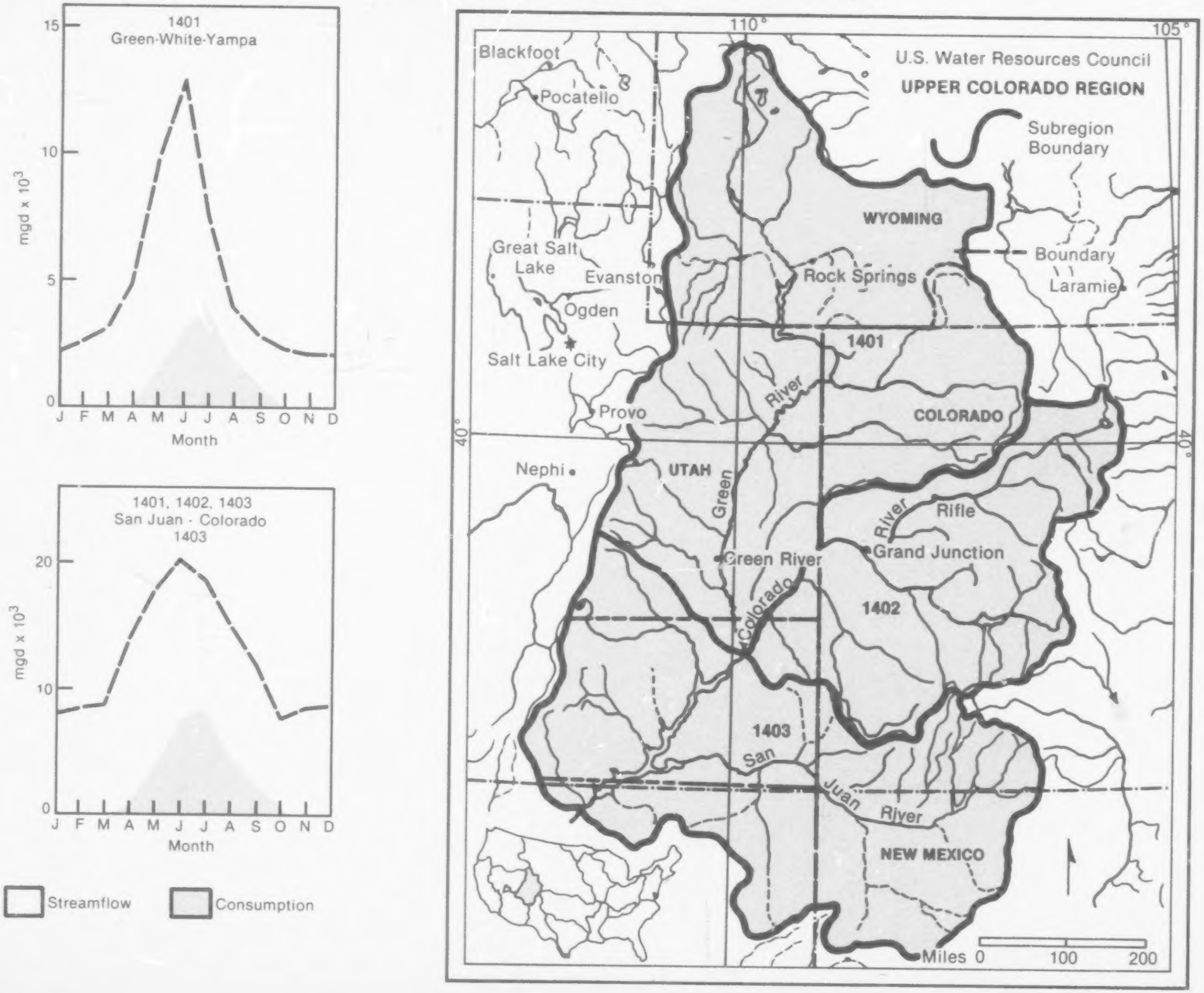
Water supply and use for the Upper Colorado Water Resources Region. For this entire region, current water supply exceeds demand during every month of the year.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals: Total (mgd)	Ground water withdrawals: Overdraft (mgd)	Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
1401	3,680	1,677	64	0	115	3,186	1,019	22%
1402	4,740	948	24	0	27	2,532	987	17
1403	10,000	702	38	0	569	1,151	434	20
Total region ..	10,000	3,328	126	0	711	6,869	2,440	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-11.—The Upper Colorado Water Resources Region


1401
Green-White-Yampa
15
10
5
0
mgd x 10^3
J F M A M J J A S O N D
Month
1401, 1402, 1403
San Juan - Colorado
1403
20
10
0
mgd x 10^3
J F M A M J J A S O N D
Month
Streamflow
Consumption
110°
105°
40°
40°
U.S. Water Resources Council
UPPER COLORADO REGION
Subregion Boundary
Boundary
Blackfoot
Pocatello
Great Salt Lake
Evanston
Ogden
Salt Lake City
Provo
Nephi
Laramie
Rock Springs
WYOMING
1401
COLORADO
UTAH
River
Green
Green River
Colorado
River
Rifle
Grand Junction
1402
1403
San
Juan
River
NEW MEXICO
Miles 0 100 200

Both water supply and use characteristics of the region vary widely between the upper and lower basins and is largely the result of a much lower population in the upper basin (344,000 v. 2,400,000 in the lower basin (1975 data)).

Normal reservoir storage in the basin is 71.5 maf, of which 61.3 maf (86 percent) are located in the lower basin. This represents 5.8 times the mean annual flow of the Colorado River, as estimated by the Second National Assessment. Ground water withdrawals from subsurface storage are estimated at 5.7 maf/year. More than 95 percent of these withdrawals occur in the lower basin and are estimated to consist of at least 50 percent of overdrafted water that is not being recharged.

Total withdrawals for the basin as a whole are 14.1 maf annually, of which slightly more than half are made in the lower basin. Consumption is somewhat less equally divided. In the upper basin, 2.7 maf are consumed annually, while in the lower basin, 5.2 maf, or almost twice as much, are consumed. Withdrawals for irrigation are 94 percent and 89 percent for the upper and lower basins, respectively, while consumption by irrigation is higher in the lower basin, 45 percent to 32 percent of total withdrawals.

Supply and use relationships for individual subregions within the upper and lower basins are shown graphically in figures B-11 and B-12. The Second National Assessment states that "The Colorado River system is one of the most controlled, overburdened, and most oversubscribed river systems in the Nation."

For individual subregions within the basin, there is an excess of water supply over water use in all subregions of the upper basin, while demand exceeds supply, often significantly, in the subregions of the lower basin. The water deficit is being made up by ground water overdrafting, which must continue if water-use patterns are not to change dramatically in the lower basin. Whether this overdrafting can be continued into the indefinite future is a matter of some speculation, given the spatially variable nature of the ground water resource and the fact that the water table is now declining at a rate of 4 to 10 ft/yr in certain critical areas of the region. With the completion of the Central Arizona Project, the Second National Assessment reports that "essentially all renewable surface and ground water supplies will . . . be utilized" and water supplies will become inadequate to meet the needs of the basin sometime before the year 2000.

Water Resources Region 15: Lower Colorado River

The relationship between supply and use in the Lower Colorado River basin. In two of the three subregions, the use of water exceeds the supply in all but one month of the year. In the Gila River subregion, which includes the cities of Phoenix and Tucson, Ariz., the imbalance between supply and use is particularly extreme.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals Total (mgd)	Ground water withdrawals Overdraft (mgd)	Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
1501	272	50	70	5	31	220	73	21%
1502	1,550	18,863	960	290	1,020	2,424	1,059	114
1503	20	1,049	3,978	2,120	151	6,273	3,463	254
Total region . .	1,550	19,962	5,008	2,415	1,202	8,917	4,595	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

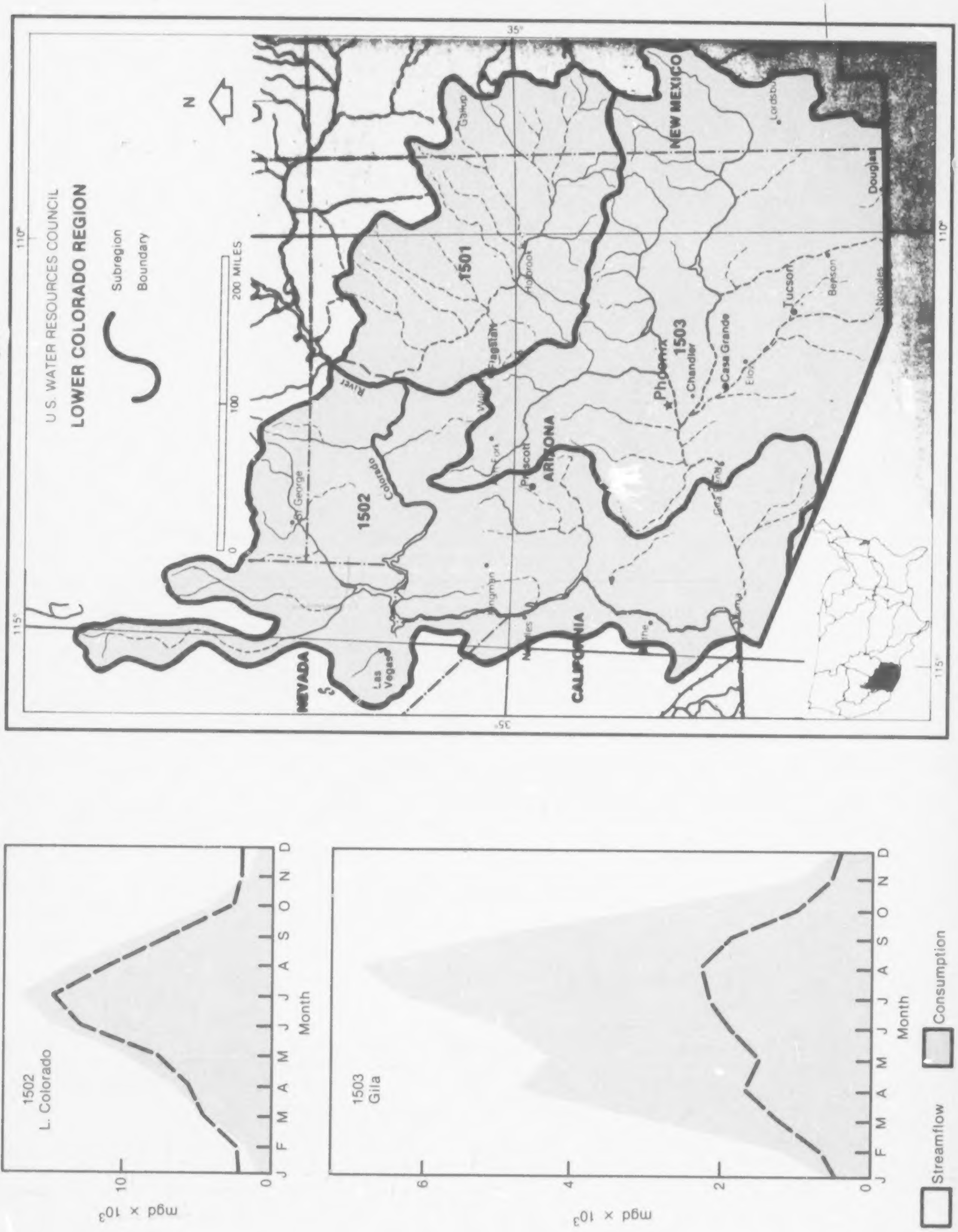

U.S. WATER RESOURCES COUNCIL
LOWER COLORADO REGION
Subregion Boundary
0
100
200 MILES
N
35°
110°
115°
NEVADA
CALIFORNIA
ARIZONA
NEW MEXICO
1501
1502
1503
St. George
Las Vegas
Needles
Kingman
Prescott
Flagstaff
Holbrook
Gallup
Phoenix
Chandler
Casa Grande
Eloy
Tucson
Benson
Nogales
Douglas
Lordsbu
Colorado
River
1502 L. Colorado
1503 Gila
mgd × 10³
0
10
2
4
6
J F M A M J J A S O N D
Month
Streamflow
Consumption

Figure B-12.—The Lower Colorado River Water Resources Region

The Great Basin: Water Resources Region 16

The Great Basin is a closed interior basin, lying between the Rocky Mountains and the Sierra Nevada Mountains of California, from which there is no drainage. All precipitation falling in the basin and all runoff entering it from the surrounding mountains must ultimately leave by evapotranspiration or, possibly, ground water runout. The Great Basin encompasses the western half of the State of Utah and virtually all of Nevada and it has a surface area of 137,000 mi^2. Mean annual runoff has been variously estimated at between 2.9 maf (5) and 8.4 maf (4). Average annual precipitation in this basin is probably less than 10 inches/yr, while potential evapotranspiration values are estimated to be several times this value. This suggests that relatively little water is available for soil or ground water recharge. The high range in the estimates of runoff into this basin results, at least in part, from a lack of actual measurements of the water produced from these many mountain sources and from a certain amount of ambiguity concerning the ratio of rain and snowfall to runoff.

Normal surface storage in the basin is 3.8 maf. Surface area storage 130,000 acres, from which 355,000 acre-ft are estimated to be lost annually to evapotranspiration. This amount represents a specific value of 2.7 ft of water annually and is approximately 12 percent of the low estimate of total annual runoff into the basin.

Available ground water resources are estimated to be approximately 525 maf, of which 1.6 maf are withdrawn annually for an estimated overdraft of 662,000 acre-ft over recharge.

Total annual withdrawals within the Great Basin are 9 maf, of which 4.2 maf are consumed. Irrigated agriculture accounts for 7.8 maf of the withdrawals (87 percent) and 3.6 maf of the consumptive losses (86 percent). The existing estimated ground water overdraft represents approximately 7 percent of total withdrawals.

It can be seen from an inspection of figure B-13 that subregions on both the east (1601) and west (1604) sides of the Great Basin have very similar water supply/use characteristics. In both cases, supply exceeds demand during winter, whereas during July to September or October, supply and demand curves are almost identical. In subregion 1602, the Sevier River basin in southeastern Utah, demand exceeds supply during almost every month of the year.

Water Resources Region 16: Great Basin

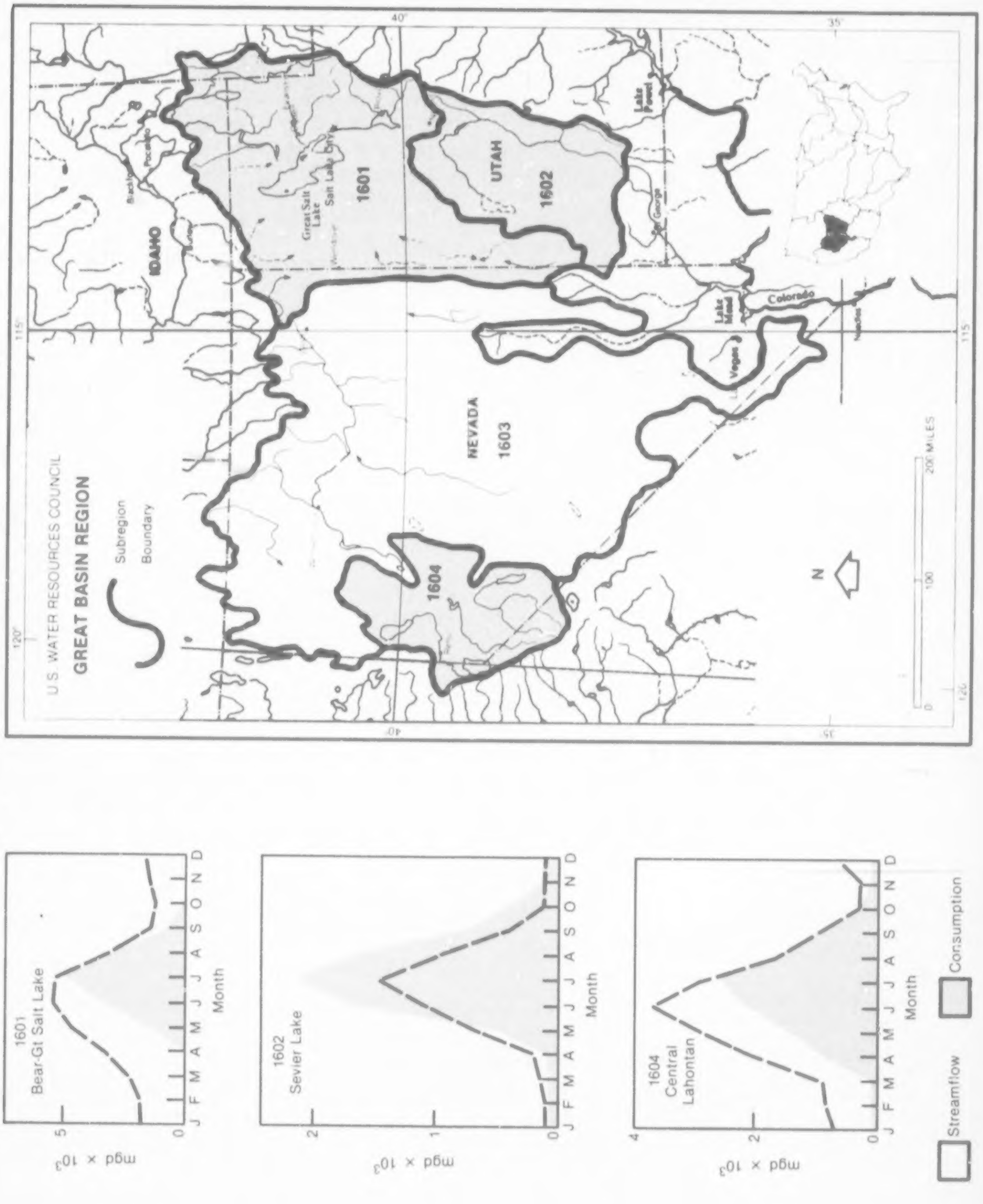
The relationship between water supply and use for the Great Basin region of Utah and Nevada. This arid area depends on the mountains to the east and west for its water supply. With the exception of the Sevier Lake subregion (1602) in southwestern Utah, where use exceeds the supply during most months of the year, there is an annual excess of water over demand. Water supply and use are equal during the summer months over the entire region.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals		Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
			Total (mgd)	Overdraft (mgd)				
1601	1,640	680	581	43	98	3,557	1,255	44%
1602	114	178	321	240	59	1,153	599	127
1603	132	144	433	286	93	1,770	1,077	117
1604	676	236	89	22	77	1,511	848	56
Total region ..	2,562	1,239	1,424	591	327	7,991	3,779	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-13.—The Great Basin Water Resources Region


U.S. WATER RESOURCES COUNCIL
GREAT BASIN REGION
Subregion Boundary
IDAHO
UTAH
NEVADA
1601
1602
1603
1604
Great Salt Lake
Salt Lake City
Pocatello
Blackfoot
St. George
Lake Powell
Lake Mead
Colorado
Vegas
Needles
N
0
100
200 MILES
120°
115°
40°
35°
1601 Bear-Gt Salt Lake
1602 Sevier Lake
1604 Central Lahontan
mgd × 10³
0
5
1
2
4
J F M A M J J A S O N D
Month
Streamflow
Consumption

The Pacific Northwest Basins: Water Resources Region 17

The Columbia River Basin, which drains sections of Montana, Idaho, Washington, Oregon, Nevada, and the Canadian Province of British Columbia, has a surface area of approximately 275,000 mi^2 (160 million acres) and discharges an estimated 235 to 286 maf into the Pacific Ocean each year. This represents approximately 50 percent of all the surface water available annually in the 17 Western States and is roughly 20 percent of all the surface discharge from the entire continental United States. Of the approximately 140 maf discharged by the Columbia River each year, nearly 50 percent enters the United States from the province of British Columbia. The remainder is largely produced by melting snowpacks in the mountains of western Montana, the Idaho "panhandle," and the east slopes of the Cascade Mountains in Washington State.

Discussions of water supply and demand in the Pacific Northwest region are complicated by the extreme variability that characterizes this region and competing uses for water. Average annual runoff depth ranges from less than 1 inch in portions of the interior of Washington State to more than 100 inches at the higher elevations of the Cascade Range along the western coast.

The region is divided into two hydrologic provinces by the Cascade Range. On the west slope of this range, water is plentiful and fairly uniformly distributed. East of the range, water is plentiful, but concentrated in channels of the Columbia River and its major tributaries, the Snake and Clark Fork Rivers, thus draining the west slopes of the Rocky Mountains in Idaho and Montana.

While the question of instream flow maintenance is not unique to this river basin, it is particularly well defined here because of the economic value of the various competing instream and offstream uses. If all competing uses are considered, the water resources of the Pacific Northwest east of the Cascade Range in the Columbia River basin, are fully used.

The normal reservoir storage in the region is 54.8 maf, which is slightly less than 20 percent of the mean annual discharge. Over 1.7 billion acre-ft are required annually for the generation of hydroelectric power in the basin. This means that all water passing through the reservoir system must be used approximately seven times for existing hydroelectric generation. While this water is theoretically available at all times for other uses, in practice, conflicts arise. Ground water withdrawals (8.2 maf/yr) are the third highest of all the water resources regions in the Western United States. Ground water overdrafting exists locally and could create local shortages in the future.

Total withdrawals (42 maf annually) and offstream consumption (13 maf anually, of which irrigation consumes almost 12.5 maf) are among the highest in the Western United States.

Figure B-14 illustrates the supply-use aspects of the basin for two selected subregions. In the Upper Snake River, use of water is within 15 percent of supply during July and August. Maximum offstream uses for the main Columbia River (subregion 1702) never exceed 30 percent of monthly streamflow. Only if instream flow requirements for the salmon fishing industry, navigation, and hydroelectric generation are factored into the supply-use question can an accurate picture of water use in the Columbia River basin be obtained. If it is assumed that the demand for electricity remains essentially constant throughout the year, the Columbia River is heavily overcommitted.

Water Resources Region 17: Pacific Northwest

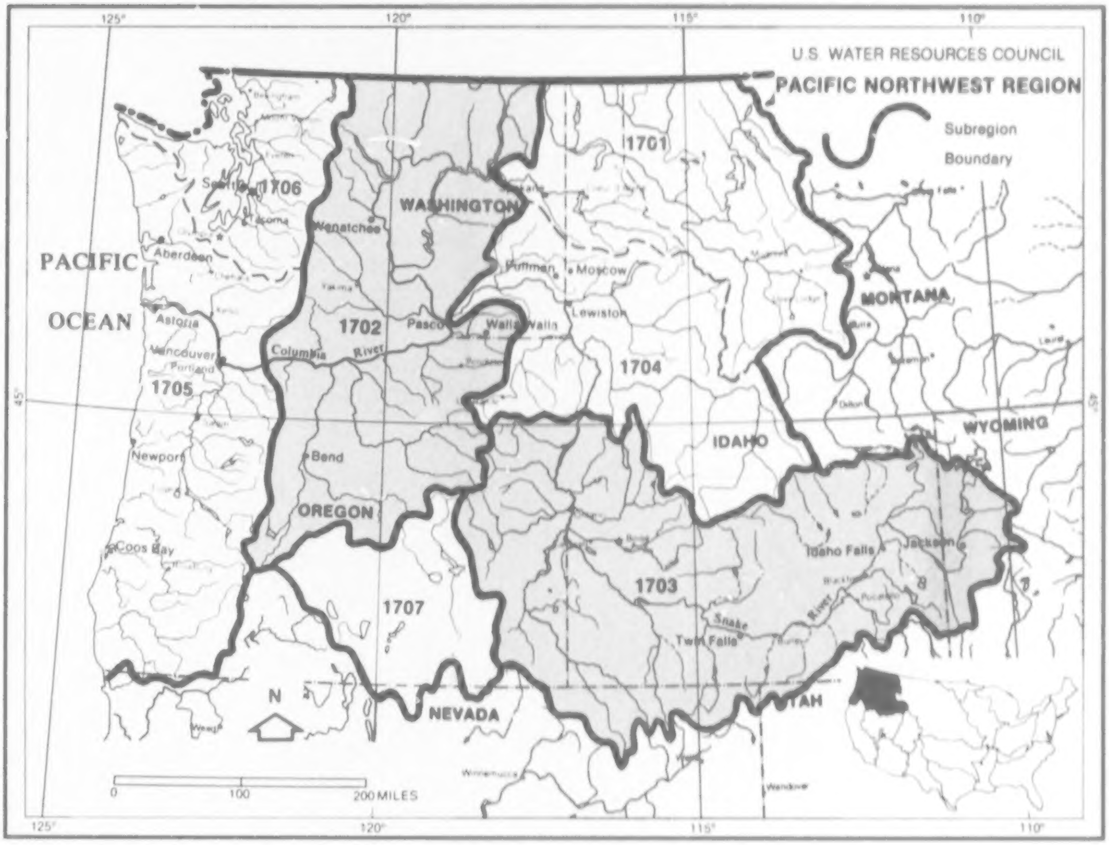
Relationship between supply and use in the Pacific Northwest region. While this region is often considered to be a water surplus area, it is apparent that along the Upper Snake River, water use is approaching supply during the summer months of each year. Along the Columbia River, the various uses to which the water is put (e.g., hydroelectric generation, fishery support, irrigation) mean that little excess water is actually available once all these demands are satisfied.

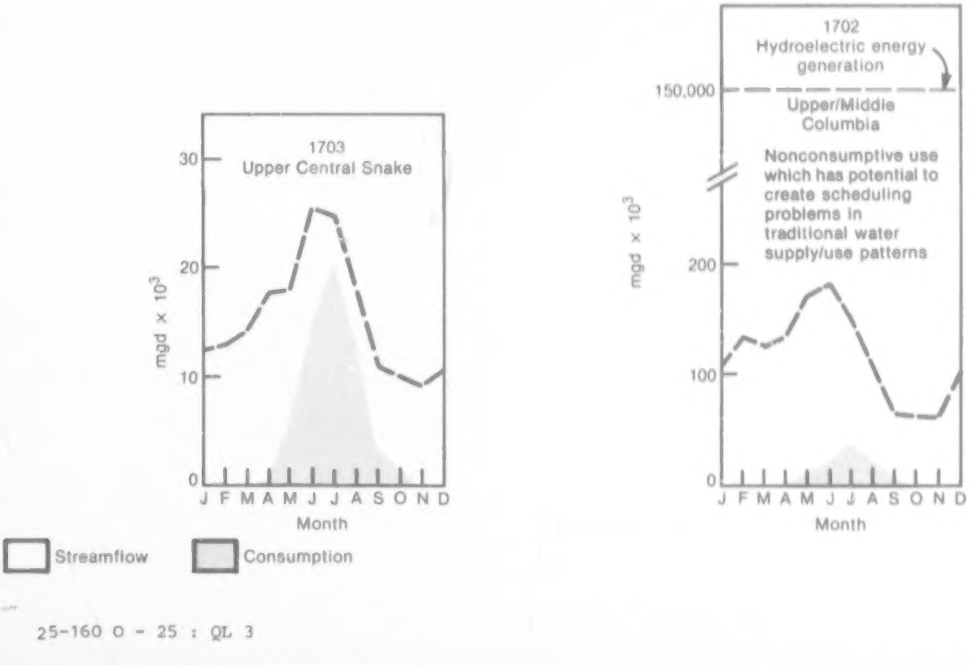
Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals		Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
			Total (mgd)	Overdraft (mgd)				
1701	31,400	3,579	242	10	406	1,924	626	2%
1702	115,000	6,107	742	332	664	7,774	4,023	8
1703	10,600	4,082	5,591	225	830	20,640	5,128	33
1704	29,700	1,061	102	30	89	1,422	439	16
1705	212,000	1,796	440	16	0	2,404	756	5
1706	42,200	1,139	178	0	0	1,098	194	1
1707	1,070	76	53	14	25	2,364	747	41
Total region ..	255,270	17,839	7,348	627	2,014	37,626	11,913	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-14.—The Pacific Northwest Water Resources Region


U.S. WATER RESOURCES COUNCIL
PACIFIC NORTHWEST REGION
Subregion Boundary
125°
120°
115°
110°
45°
PACIFIC OCEAN
1701
1702
1703
1704
1705
1706
1707
WASHINGTON
OREGON
IDAHO
MONTANA
WYOMING
NEVADA
UTAH
Seattle
Tacoma
Aberdeen
Wenatchee
Pullman
Moscow
Lewiston
Pasco
Walla Walla
Columbia River
Astoria
Vancouver
Portland
Newport
Bend
Coos Bay
Idaho Falls
Jackson
Snake River
Twin Falls
N
0
100
200 MILES



The California Basins: Water Resources Region 18

The California region includes the State of California and Klamath County, Ore. It has a total surface area of approximately 160,000 mi² and a mean annual surface runoff variously estimated at between 53 maf/yr (5) and 69 maf/yr (4). According to WRC, approximately 85 percent (45 maf/yr) is discharged from two subregions in the northern portion of the State, the Klamath and Sacramento Rivers. At the same time, more than half of the approximately 21 million inhabitants of the State live in subregion 1806, which includes the metropolitan areas of Los Angeles and San Diego. This subregion has an annual discharge of 6.5 maf annually, slightly more than 10 percent of the total runoff of the State (5). The fact that significant amounts of irrigated agriculture also exist in the southern half of California, principally in the San Joaquin Valley, only serves to compound the severe water supply-use imbalance in the State.

Normal reservoir storage for California as a whole is approximately 39 maf, which is equivalent to less than 75 percent of the smaller of the two estimates of total streamflow. The California water resources region ranks first among those in the Western United States in terms of total water withdrawals (44.4 maf), total ground water withdrawals (21.5 maf), total water consumed (29.8 maf), and total water consumed by irrigation (27.2 maf).

A comparison of supply-use curves for northern and southern subregions within the State illustrates the imbalance (fig. B-15). In the Sacramento River basin (1802), in spite of extensive irrigated agriculture, water supplies exceed uses during all months of the year. In two southern basins, the San Joaquin River and the Los Angeles-San Diego basins, water demand slightly exceeds surface supplies during almost every month of the year. There appears to be no water available for future development in the southern portion of the State without some change in water supply or use patterns.

Water Resources Region 18: California

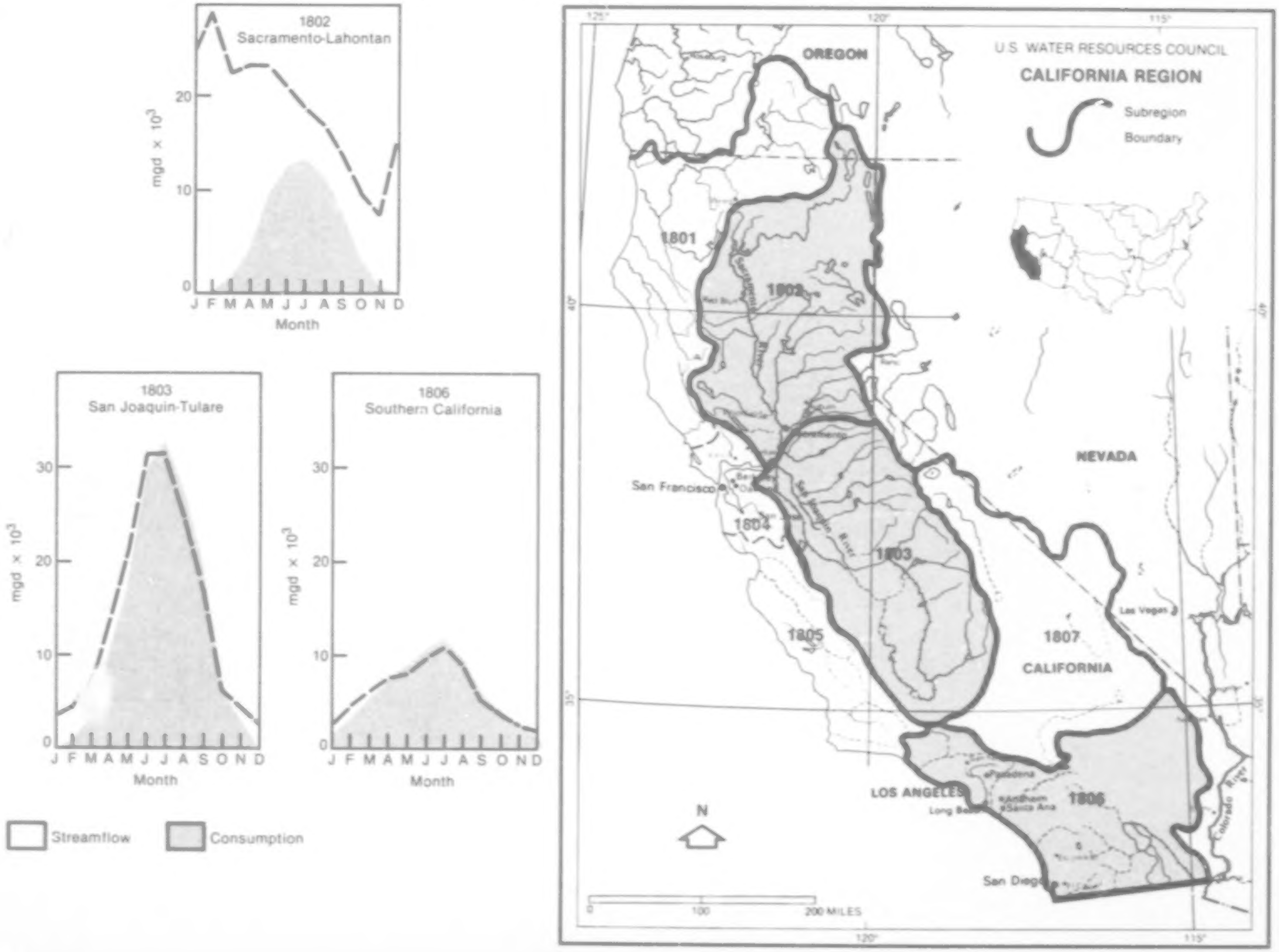
The relationship between water supply and use for selected subregions in the California region. This is a graphic illustration of the water imbalance between the northern and southern portions in California. In a northern subregion (the Sacramento), supply exceeds use during all months of the year, while in the central San Joaquin-Tulare and southern California subregions, virtually all available water is used during every month of the year.

Subregion	Mean streamflow (mgd)	Normal surface storage (bg)	Ground water withdrawals		Evaporation from reservoirs, stockponds (mgd)	Withdrawals (mgd) (fresh and saline)	Total consumption (mgd)	Offstream use to total streamflow (mgd)
			Total (mgd)	Overdraft (mgd)				
1801	26,000	1,298	181	0	0	2,256	737	3%
1802	13,900	5,446	4,052	233	138	7,756	5,398	28
1803	2,830	3,717	10,659	1,250	315	17,828	12,649	89
1804	2,570	790	616	0	13	7,744	809	24
1805	1,490	412	1,181	83	20	3,999	833	37
1806	446	850	2,020	491	137	14,168	5,887	101
1807	139	183	451	140	46	454	328	100
Total region	47,375	12,697	19,160	2,197	669	54,205	26,641	

Key: mgd = million gallons per day (multiply by 1,120 to obtain acre-ft/year). bg = billion gallons (multiply by 3,070 to obtain million acre-ft).

SOURCE: Second National Water Assessment, 1978.

Figure B-15.—The California Water Resources Region


1802
Sacramento-Lahontan
1803
San Joaquin-Tulare
1806
Southern California
mgd × 10^3
0
10
20
30
J F M A M J J A S O N D
Month
Streamflow
Consumption
U.S. WATER RESOURCES COUNCIL
CALIFORNIA REGION
Subregion Boundary
OREGON
NEVADA
CALIFORNIA
1801
1802
1803
1804
1805
1806
1807
Sacramento River
San Joaquin River
Colorado River
San Francisco
LOS ANGELES
Long Beach
Pasadena
Anaheim
Santa Ana
San Diego
Las Vegas
N
0
100
200 MILES
125°
120°
115°
40°
35°

Ground-Water Resources Regions

The availability, ease of extraction, and total quantity of ground water present at a site is determined largely by the local geology, climate, and surface hydrologic regime. While climate and the surface hydrologic regime commonly vary together at a site, the geology, which determines the extent to which rocks will hold and transmit ground water, often varies independently of the surface environment. For this reason, ground-water resources regions do not necessarily correspond to surface-water resources regions. In assigning an area to a given ground-water resources region, arbitrary decisions must often be made concerning the relative importance of climate and geology. For the purposes of this assessment, the delineation of these regions used is that originally developed by Thomas and subsequently adopted by others (1). The general location these regions in shown in figure B-16. They are:

1. Western Mountain Ranges,
2. Alluvial Basins,
3. Columbia Lava Plateau,
4. Colorado Plateaus and Wyoming Basin,
5. High Plains,
6. Unglaciated Central Region, and
7. Glaciated Central Region.

Western Mountain Ranges

The Western mountain ranges, consisting primarily of the Rocky Mountains and the Cascade and Sierra Mountain ranges near the Pacific Coast, serve as the principal source of water in the Western United States because the bulk of the regional precipitation falls here and resulting runoff supplies streams and aquifers. Rocks in the region are generally hard and dense. They shed water rather than absorbing it and ground water is limited although some ground water may be extracted from alluvial materials, sands, and gravels, filling the floors of small intermontane valleys.

Most local water supplies are obtained from springs, wells in valleys, and surface reservoirs. Not enough wells have been drilled in the higher mountains to establish any trends in ground water availability, although the character of the rocks there indicate that such water may be obtained from fractured areas. Because of the limited human use of the Western mountains ranges, no widespread water-quality problems have been mentioned in the literature.

Alluvial Basins

Alluvial basins are found in a southwestern tier of States reaching from California to central New Mexico. They reach as far north as northern Nevada and include portions of western Utah and southern Arizona. The basins in this region consist of erosional materials removed from the adjacent mountains and deposited as alluvium in the basin floors. This alluvial material is composed of interbedded sands, gravels, and clays and is recharged principally by streams flowing across it that originate in the surrounding highlands. The alluvial fill functions as an ideal aquifer and creates an opportunity for development of high-yielding wells.

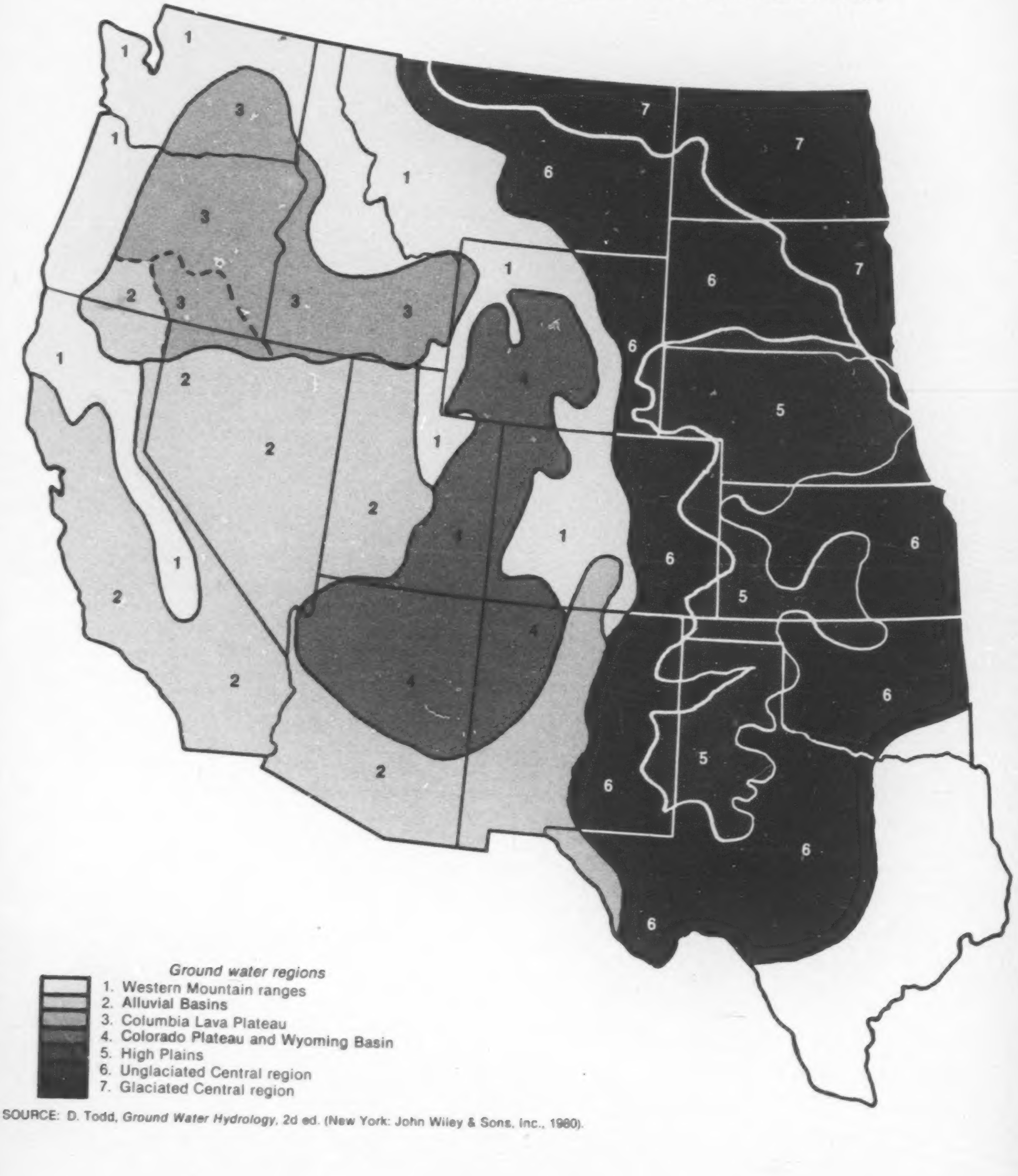
Ground water development for irrigated agriculture has been extensive in this region because of the prevailing arid climate. The rate of recharge of these aquifers is generally much less than the rate at which water is extracted from this source, and ground water levels are declining as the amount of water in storage is depleted. The local significance of this problem varies, depending on the amount of ground water use and the source and volume of the recharge water. Locally, artificial recharge has helped alleviate the problem of ground water depletion.

Ground water is a very important source of water in this region, where surface runoff is generally nonexistent over a large percentage of the area. For example, in Arizona, 61 percent of the total water use is derived from ground water. Given the extent to which this resource is being consumed and contaminated in the areas of highest use, there is legitimate cause for concern regarding the future potable water availability in some portions of the aquifers underlying the major population centers of this region (see ch. IV for a discussion of general water-quality problems affecting or likely to affect the West).

Locally, in such areas as Phoenix and Tucson, Ariz., the alluvial aquifers are intensively used. It is estimated that in Maricopa County, which includes the City of Phoenix, ground water use was 30 times the rate of natural recharge. For Pinal County, ground water depletion was estimated to be 12 times the rate of recharge. In the Tucson valley, the rate of overdraft is three to one.

For California, the largest user of ground water in this region, ground water supplies about 48 percent (21.5 maf) of the total annual freshwater withdrawals in the region, representing an estimated

Figure B-16.—The Major Ground Water Regions of the Western United States


Ground water regions
1. Western Mountain ranges
2. Alluvial Basins
3. Columbia Lava Plateau
4. Colorado Plateau and Wyoming Basin
5. High Plains
6. Unglaciated Central region
7. Glaciated Central region

SOURCE: D. Todd, *Ground Water Hydrology*, 2d ed. (New York: John Wiley & Sons, Inc., 1980).

overdraft of 2,197 million gallons per day (2.5 maf/yr), or 11.5 percent of estimated average annual recharge.

A number of ground-water quality problems have been identified in this ground-water resource region by Federal and State agencies, including the intrusion of seawater into aquifers as the result of overdrafting of ground water, water-quality degradation from percolation of irrigation waters, and localized pollution of ground water from industrial and municipal sources.

The availability of large quantities of ground water has been a significant factor in the economic growth of the Southwestern United States. The continued availability of this resource for existing uses, given the extent to which it is being "mined" and the potential for serious pollution from both agricultural, municipal, and industrial sources, is questionable.

Columbia Lava Plateau

This ground-water resource region is located principally in eastern Washington and southern Idaho. Geologically, it was formed largely by surface volcanic rocks, mainly lava flows, interbedded with or overlain by alluvium and lake sediments. Water originates chiefly from the mountains to the east and west of the Plateau, the Cascade and Rocky Mountain ranges. The lava flows tend to be highly permeable, as a result of cracks which formed at the time the lava cooled, and thus form highly productive aquifers. Large volumes of excess ground water discharge as major springs are the source of surface rivers that drain into the Snake and Columbia Rivers. Ground water is most readily available in the valley bottoms because of the great thickness of the lava flows. In the higher plateau areas, however, deep wells may be required to extract ground water for irrigation.

No widespread water-quality problems have been reported for this region. The Water Resources Council estimates that approximately 8.2 maf of water are withdrawn annually from the ground water storage in this region, representing an estimated 8.5 percent overdraft, or 70,000 acre-ft in excess of natural annual recharge. This overdraft may be localized, however; USGS states that "[o]n the Snake River Plain in Idaho, . . . excess irrigation water has filtered into the ground and joined the original ground water body, increasing the rate of recharge of ground water into the Snake River by nearly 50 percent. In this area as a whole, . . . water has not been mined, it has been put in the bank" (1).

Colorado Plateaus and Wyoming Basin

The Colorado Pleateus and Wyoming Basin region is located in southwestern Wyoming and in the Four Corners region of portions of Utah, Arizona, Colorado, and New Mexico. The aquifers in this region consist of consolidated rocks that are generally horizontal but have been folded, tilted, or fractured in places. This region is arid to semiarid, generally at an altitude high above sea level, and deeply dissected by the rivers and streams flowing through it. Prospects for large-scale ground water development are poor. Small water supplies for domestic and livestock purposes are generally available, however. Most aquifiers are sandstone beds, although limestone and alluvium also yield water in a few places. No estimates exist of ground water consumption specifically for this resource region. It is assumed to be low, since there is limited water to be withdrawn from ground water storage. Ground water quality problems identified by the Second National Assessment for this region include high levels of dissolved solids and contamination by toxic industrial wastes in portions of Colorado and New Mexico.

The High Plains (Ogallala Aquifer)

Probably the best known aquifer in the Western United States is the High Plains, or Ogallala, aquifer. This ground-water resource region includes most of Nebraska and Kansas and portions of eastern Colorado, New Mexico, and the Texas and Oklahoma panhandle. The problems of the Texas, Kansas, and Oklahoma sections of the aquifer have come to typify, for the press and public, some of the problems represented by ground water overdrafts.

In portions of Colorado, Nebraska, Texas, Oklahoma and Kansas, alluvium forms a vast plain extending eastward from the Rocky Mountains. The bulk of it is classified as a single stratigraphic unit, the Ogallala Formation, which covers older rocks to thicknesses exceeding 450 ft. The sand and gravel of the formation constitute an aquifer that may yield as much as 1,000 gallons per minute, locally. The region is generally semiarid so that ground water recharge from precipitation is extremely small. The productiveness of wells has encouraged pumping of ground water, however, especially for irrigation in Texas. This water has been derived primarily from storage. As a result, water tables have declined substantially since extensive pumping began in the 1950's.

The Ogallala aquifer has been used to support irrigated agriculture in the high plains of Texas since the development of suitable high-speed engines and turbine centrifugal pumps in the mid-1930's. Significant use of the ground water resources of the southern portion of the aquifer did not begin until the 1950's, however, spurred by the development of center-pivot sprinkler systems and the availability of low-cost natural gas. Even though the problem of overdrafting the Ogallala aquifer was recognized almost from the outset of extensive agricultural use, pumping from the aquifer increased from 1.9 maf in 1950 to 11.1 maf in 1975 in the Texas portion of the aquifer alone.

Some elements of the ground water problem in the High Plains region are generally instructive for other portions of the Western United States where the future of ground water resources is in doubt. Ground water mining has widely differing effects, even within an area that is relatively homogeneous with respect to geology, climate, and agricultural use. Throughout the High Plains region, the ground water source is referred to as a single aquifer. However, the properties and characteristics of that aquifer vary greatly from Nebraska to the Texas panhandle, and ground water is unevenly distributed within and among the individual States. Depending on the configuration of the aquifer and its physical composition, individual areas will be affected very differently by ground water mining.

The dewatering of the Ogallala aquifer has had the most serious consequences in the Texas, Oklahoma, Kansas, and Colorado portions, where the aquifer is thinner, the saturated thickness is less, and the permeability is generally lower. Even there, however, the natural variability of the aquifer has produced water level declines ranging from 20 to more than 120 ft, so that there is no single impact on irrigated agriculture. In the northern portion of the aquifer, primarily Nebraska, the saturated thickness is up to 10 times that of the southern portion, and nearly 60 percent of all the water contained in the aquifer is found there (3). Even in this relatively water-rich portion of the aquifer, ". . . the ground water pinch is prompting officials to consider allocating available ground water by metering it in control areas of the Natural Resources District" (2). In spite of the overall volume of water in the northern portion of the aquifer, there have been water-level declines in some areas necessitating deeper wells and higher pumping lifts with increased pumping costs. The continued use of the large volumes of water required by irrigated agriculture in the northern portion of the Ogallala aquifer will become increasingly affected by institutional and economic factors, such as the legal status of ground water and energy costs.

Unglaciated Central Region

This is a large and complex ground-water resource region, extending from southern New Mexico to the southeastern portion of Montana, from east of the Rocky Mountains to east of the High Plains region in central Texas, Oklahoma, and the southeastern corner of Kansas. It is an area of plains and plateaus underlain by consolidated rocks. Alluvial deposits of substantial width and thickness form good aquifers along the Arkansas, Platte, and Missouri Rivers but are not generally important elsewhere. Aquifers in most of the region are composed of limestone or sandstone with low to moderate yields. Some of the most unproductive aquifers in the Western United States are found in this region because of low water yields, high salinity, or a combination of both. On the other hand, wells drilled into cavernous limestone may yield large amounts of high-quality water. This extreme local variability makes generalizations concerning ground water availability or quality in this region unreliable. Local testing is required to establish the values for both. Except locally, ground water does not represent a major source of water in the region.

No problems with ground water availability for this region were discussed in the Second National Water Assessment. Water-quality problems, generally involving high levels of salinity, are identified for portions of central Texas and Oklahoma.

Glaciated Central Region

This region is quite similar to the Unglaciated Central region except for the mantle of unconsolidated deposits of the ice and meltwaters of the continental glaciers that covered it at one time. It includes the northern portion of Montana, much of North Dakota and eastern South Dakota, and a small portion of northeastern Kansas. The glacial materials consist mostly of fine-grained rock debris intermixed with beds of sands and gravels. In portions of the area, the glacier material is nearly 1,000 ft thick and forms an important aquifer. In this region, large-diameter wells yield sufficient water to meet domestic needs.

Hazardous Waste Sites by State

Arizona:	
Scottsdale	Indian Bend Wash Area
Kingman	Kingman Airport Industrial Area
Goodyear	Litchfield Airport Area
Globe	Mt. View Mobile Home* **
Tucson	Tucson International Airport*
Phoenix	19th Avenue Landfill*
California:	
Rancho Cordova	Aerojet*
Hoopa	Celtor Chemical
Ukiah	Coast Wood Preserving
Redding	Iron Mountain Mine*
Sacramento	Jibboom Junkyard
Richmond	Liquid Gold
Fullerton	McColl
Cloverdale	MGM Brakes
Fresno	Purity Oil Sales, Inc.
Fresno	Selma Pressure Treating
Glen Avon Heights	Stringfello**
Colorado:	
Leadville	California Gulch
Idaho Springs	Central City, Clear Creek*
Denver	Denver Radium Site*
Boulder	Marshall Landfill* **
Commerce City	Sand Creek
Commerce City	Woodbury Chemical*
Idaho:	
Rathdrum	Arrcom (Drexler Enterprises)
Smelterville	Bunker Hill
Caldwell	Flynn Lumber Co.
Kansas:	
Arkansas City	Arkansas City Dump* **
Holiday	Doepke Disposal, Holiday
Wichita	John's Sludge Pond
Cherokee County	Tar Creek, Cherokee Co.
Montana:	
Anaconda	Anaconda—Anaconda
Libby	Libby Ground Water
Milltown	Milltown
Silver Box/ Dear Lodge	Silver Bow Creek
North Dakota:	
Southeastern	Arsenic Trioxide Site* **
Nebraska:	
Beatrice	Phillips Chemical
New Mexico:	
Clovis	ATSF/Clovis*
Milan	Homestake*
Albuquerque	South Valley* **
Churchrock	United Nuclear Corp.*
Oklahoma:	
Criner	Criner/Hardage*
Ottawa County	Tar Creed*
Oregon:	
Portland	Gould, Inc.
Albany	Teledyne Wah Chang
South Dakota:	
Whitewood	Whitewood Creek* **
Texas:	
Grand Prairie	Bio-Ecology*
Houston	Crystal Chemical*
Crosby	French, Ltd.*
Houston	Harris (Farley St.)*
Highlands	Highlands Acid Pit*
La Marque	Motco* **
Crosby	Sikes Disposal Pits*
Orange County	Triangle Chemical
Utah:	
Salt Lake City	Rose Park Sludge Pit* **
Washington:	
Spokane	Colbert Landfill
Tacoma	Commencement Bay, Near Shore Tide Flat*
Tacoma	Commencement Bay, S. Tacoma Channel*
Wyoming:	
Laramie	Baxter/Union Pacific

* = IPL/EEL. ** = States' Designated Top Priority Site.
"IPL" means the Interim Priorities List of 115 sites announced in October 1981. "EEL" refers to the Expanded Eligibility List, an additional 45 sites designated in July 1982 as eligible for remedial actions.

SOURCE: U.S. Environmental Protection Agency, *Hazardous Waste Sites by State, Proposed Superfund Priorities List*, December 1982.

Appendix B References

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Appendix C

Institutions

Note: The information in this appendix further elaborates on material presented in chapter V.

State Initiatives in Water-Resources Planning

Early State involvement with water rights in the Western States related to allocating water rights to individuals as property rights. As discussed in chapter V, the "distributive" character of early water-resources projects required local consent. A number of economic benefits accrued to States; there were also some less obvious disadvantages. The impetus for development of specific water-resource projects usually came from the Federal agencies which had expertise and planning capacity and was triggered by demand or crises.

In the early days of reclamation projects, States generally deferred to Federal agency initiatives in large-scale water-resources development. These agencies, staffed largely by engineers, were expert in large dam and related construction projects. Decisions on project development were essentially political and rarely involved difficult technical benefit-cost evaluations (e.g., esthetics, noneconomic impacts), realistic repayment plans, or consideration of potential alternatives, such as changing patterns of settlement or behavior, to meet development goals. In 1964, the Executive Secretary of the Upper Colorado River Basin, speaking generally about the States, observed:

> Many States have poor organizations for long-range planning and their water resource agencies lack financial support. Some States even appear to lack the proper agencies that can do their share of the overall planning job. In many instances, initiatives in planning rests with Federal agencies. State and local governments are often in a position to approve or disapprove plans without having made adequate studies for major decisions needed in the field of water resources. (U.S. Senate, 1964, in ref. 18)

In the 1960's and 1970's a number of events combined to begin a gradual shift to more active State roles. Local perceptions began to change about environmental values associated with water, and these views were voiced by local groups to local politicians. Environmental impact statements and water-quality standards brought more expertise to the State level as State agencies became more aware and involved with local impacts of development. Federal funding for capital-intensive water projects showed signs of diminishing. Federal funds and planning assistance became available through such mechanisms as the Water Resources Planning Act of 1965 and the Office of Water Research and Technology (OWRT) within the Department of the Interior to help States build their own water research capabilities.

The result has been a growing and increasingly visible level of State interest, awareness, and involvement in water-resources planning and management. For example, in November 1982 the National Conference of State Legislatures (NCSL) issued a detailed and well-documented report, *Water Resources Management: Issues and Policy Options,* to assist State legislatures formulate water-related policies and programs (17). Though State efforts have varied, three kinds of activities help illustrate this shift:

1. protecting instream uses,
2. dealing with conflicting uses of water, and
3. water-resource planning and regulation.

Water for Instream Uses

Multiple use of a State's water resources is advocated by most States. Within the last 10 to 15 years, this concept has taken on a new dimension in the form of minimum streamflows to protect and preserve instream values for fish, wildlife, and recreational purposes. While it is true that some of these programs are modest in nature, they reflect a shift in traditional State policy. It is somewhat ironic that efforts to preserve instream flows come at a time when most States are experiencing even greater demands for additional diversions from the streams for other uses. This has and will make the task of protecting instream values much more difficult. Nevertheless, considerable amount of activity is occurring with respect to nonconsumptive uses such as minimum streamflow protection with potential important implications for sustaining and advancing agricultural uses of water at the State level.

The type, scope, and strength of the various State programs in this field vary greatly. For example, California has adopted, among other strategies, a State version of a wild and scenic rivers act. Colorado, Idaho, and Montana have enacted legislation that allows administrative agencies to protect certain instream values by reserving water for this purpose. Oregon, one of the first States to recognize instream values, created a Water Policy Review Board in 1955 with powers to set minimum perennial streamflows sufficient to support aquatic life and minimize pollution. Utah allows the State Engineer to consider the natural stream environment when evaluating new applications to appropriate water. Other States have charted different courses.

In application, protecting instream flows involves tradeoffs with existing water uses. As such, decisionmaking to protect such flows has been difficult and complicated even where authority exists. For example, while the Oregon Water Board has had the authority to classify and allocate water for instream flow purposes, instream rights are a lower class than the water rights granted prior to the 1955 enactment and thus are junior to most of the water rights in the State. Taking administrative action to protect instream flows would involve changing actual or allocated offstream uses. Consequently, according to one policy expert, minimum instream flow protection in Oregon has not been guaranteed under the 1955 legislative authorization (19).

Resolving Problems of Conflicting Uses

States are becoming increasingly involved in resolving conflicting uses of water. Water scarcity plus rising water demands have brought forth a variety of attempts at the State level to reallocate or transfer private water rights. A few State experiences illustrate some of the approaches being taken:

1. Arizona, where a comprehensive legislative framework is being used to allocate and reallocate water rights;
2. a subbasin in New Mexico, where a local water district is expanding its traditional functions; and
3. Colorado where economic, market-oriented procedures are used to resolve water conflicts.

Arizona relies on ground water supplies and since the 1930's has been "mining" this resource. In the 1970's, as use conflicts grew and competitors turned increasingly to the courts to protect their interests, legislation was passed mandating the development of a Groundwater Management Study Commission composed of legislators and representatives from mining, municipal, and agricultural interests to rewrite the ground water code. Pressure also came from the Secretary of the Interior, who indicated that his recommendations on the Central Arizona Project water allocations would be positively influenced by strong ground-water law reforms.

The Arizona Groundwater Management Act was passed on June 12, 1980,* creating the first comprehensive legislative framework for management of ground water resources in Arizona. It established active management areas (AMAs) in parts of the State, where, owing to the magnitude of ground water pumping, active ground water management was necessary to ensure long-term supplies. Management plans detailing water duties and approved water-use practices are required for each AMA. The act allowed all legal ground water pumping that had existed at the time the act was passed to continue. It called for validation of such grandfathered rights, the issuance of permits under certain criteria for new rights, and restriction on new irrigated acreage. Because the goal of the act is to eventually balance ground water withdrawals with the safe yield of aquifers, new uses will depend on the willingness of existing uses (in other words, irrigated agriculture) to sell their water rights. This will have significant ramifications on land use in Arizona and the future of agriculture in the State (3).

The *middle Rio Grande basin of New Mexico* has been the setting for growing conflict between the historical, rural character of the State and the modern demand for transfer of water rights to industrial and municipal uses. Originally, this basin was almost exclusively devoted to agriculture. Now it has become the largest urban center in the State. Thus, the principal agricultural institution in the area—the Middle Rio Grande Conservancy District—has come under increasing pressure to accommodate these new uses (3).

Because of competing uses, a market for water rights has developed in the basin. Since water rights were originally attached to agriculture, any reduction or diminution of these rights threatens the traditional role of the basin's Conservancy District. The district became involved with litigation as it tried to protect agricultural water rights and prevent transfers from within the district's boundaries to a new owner and use outside the boundaries. It has considered the prospect of leasing its water to other uses of higher economic value in the urban area. The district might become more involved with use of its existing agricultural rights to offer recreational and related amenities to the urban population through more active management of its lands and water as "greenbelt" areas in the urban vicinity. Whether such a shift to multiple-use management is possible depends on the speed with which the district can assume a new role as regional water

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*Ariz. Rev. Stat. Ann. secs. 45-401 to 636 (Supp. 1981-82).

Photo credit: © Ted Spiegel, 1982

A suburb in Tucson, Ariz., an area of extensive ground water overdraft, with a major interest in domestic, urban, and industrial water use, where agriculture may become a lower priority.

manager to provide the new kinds of services required.

Colorado has had some of the most extensive experience with water transfers as a means of dealing with conflicting uses. Colorado water law allows the free transfer of private water rights as long as third- party rights are protected. This provision has resulted in the development of largely economic, market-oriented procedures. Over the last 20 years large transfers of water from the agricultural sector to municipal and industrial uses have been made. Purchases of agricultural rights have been particularly active for the Colorado communities along the eastern side of the Rocky Mountains (the "Front Range"). Shifts are even more evident in the use of water from the Bureau of Reclamation Colorado-Big Thompson (CBT) project. In 1957, 15 percent of the project water was owned by municipalities; by 1978, municipalities owned 34 percent (3).

At the same time, Colorado is a Western State that recognizes environmental interests. In 1973 changes were made in the State's constitution and water laws recognizing instream use of water as a beneficial use and allowing the State to appropriate or purchase water rights for such use. The large shifts in water use plus these emerging social values resulted in the commissioning in 1976 of a Colorado Water Study to analyze "future water allocations . . . in terms of their impacts upon values of fundamental concern to broad segments of society" (4).

A major purpose of the Colorado Water Study was to look at the State's water-allocation practices in the context of water scarcity and the growing pressures of economic growth, energy development, and increased population. Of particular concern was the loss of the economic base which irrigated agriculture represented and the "rural lifestyle" associated with the agricultural way of life. The concern focused on whether unrestricted water transfers for solely economic values are also adequately serving other important values such as the rural lifestyle and environmental preservation (4).

Many new demands for water are being placed on Colorado's water supply. As transfers continue to be proposed, some may be found detrimental to the present instream flow values when they involve a change in use or change in point of diversion. The instream flow classification as a beneficial use may provide a mechanism whereby noneconomic considerations could be incorporated into a basically market-oriented water-allocation process.

Water-Resource Planning and Regulation

State water-resource management programs have never been more in need as traditional water uses grow and compete with rapidly accelerating demands for water for energy development and instream flows. Opportunities to stretch available water resources in the foreseeable future are going to come primarily from better water resources management programs at the local level.

The development of a State water plan is an important step in minimizing friction between competing interests for available water while advancing overall public interest. Some Western States have begun to develop water-planning mechanisms. The preparation of water plans can be expensive and requires a good deal of time and the input of many people representing different disciplines and interests. For any plan to be effective, competing interests must perceive a full and fair opportunity to advance their views. Moreover, the resulting management decision must reflect a balanced approach that adequately takes into account differing views and local interests. According to some Western law experts, a planning process should proceed under State guidelines that are mandated by law and become part of the state regulatory program (7).

Utah is one of the States actively debating the development of a comprehensive approach to water-resources planning and management. Since 1975 it has been considering possibilities for a statewide water plan (6). The proposed plan is a combined system of planning and regulation through integrated management of water within hydrologic units. The elements of the 1975 proposed plan noted here are illustrative of the kinds of considerations likely to be faced by many Western States as they attempt to manage their limited water resources among competing uses.

In the 1975 proposal, the Utah statewide water plan would emerge through the preparation of separate unit plans for hydrologic units in the State. The unit plans would involve a substantial amount of local participation and would be under State supervision, with general guidelines and criteria applicable on a statewide basis. Once completed and approved at the State level, the various unit plans would have a regulatory status and would guide water management in their respective areas until modified. The plan would cover all uses, including agriculture.

The Utah proposed plan has several key elements for managing water resources. It incorporates water-quality considerations into the development of the plan, using the expertise of water-quality officials. The hydrologic unit plans, once adopted would serve as a regulatory as well as a planning tool. In addition, any prospective appropriator (whether an irrigator, municipality, or industry) could examine the unit plan for the particular hydrologic unit of interest and immediately determine whether there were any unappropriated water or rights available for purchase or transfer.

The Utah Legislature did not adopt the plan in 1975 because of concern by many—principally those owning irrigation water rights—that there might be some impairment or adverse impact on their water rights if they were brought within the hydrologic unit plans and a statewide plan. According to the drafters of the plan, however, any vested water rights would be entitled to the protection of constitutonal due process and would not be impaired or taken without payment of just compensation (7). The position of those who advocate the plan has been that an integrated hydrologic/regulatory approach may be one of the best prospects for protecting, sustaining, and perhaps expanding the use of water for irrigated agriculture in the arid and semiarid States (7).

Studies of the Economic Values of Western Water*

The Economic Value of Water for Irrigation

The direct value of water in irrigation is measured in terms of the increment of profit to the producer *with* irrigation as compared to profits *without* irrigation. Several methods may be employed to make this calculation. One is an "ex ante" (before the fact) approach, which computes the change in net income from assumptions about crop prices, yields, production technology, and production costs. An alternative technique may be labeled "ex post" (after the fact), which relies on statistical analysis of actual production data. The ex ante method is often most convenient for planning in specific cases, and is generally used by the Bureau of Reclamation and other Government agencies that deal with water. Various statistical approaches serve to validate the analytic measures, and are regarded by many analysts as more reliable owing to their base in "real, observable data." Any analytic measures—ex ante or ex post—can be abused by improper assumptions about prices, yields, and/or input requirements, or some cost items that may be ignored. Experience has shown, however, that when properly performed, the methods yield similar results.

What is the value of irrigation water? The value of the marginal unit of water may reflect water scarcity as well as the cost of supplying the marginal unit. Local production conditions such as rainfall, temperature, length of growing season, and market situations will also have an impact, so considerable variation in water value across the West can be expected. Highly productive areas such as the Imperial Valley or the San Joaquin Valley in California will have high values for water. Marginal production areas such as the high meadows of Wyoming will show low values.

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*Excerpted from: R. Young, "Allocating the Water Resource: Market Systems and the Economic Value of Water," OTA commissioned paper, 1982.

Beattie and Frank (2) used 1974 census data as the basis for a statistical analysis of agricultural output. One of their purposes was to learn how agricultural output is influenced by resource inputs, including land, labor, machinery, chemicals, and irrigation water. The results yielded water values (expressed in current 1982 dollars) of $10 to $15/acre-ft in the intermountain valleys of the Upper Colorado and Snake River basins; $20 to $25/acre-ft in the desert Southwest and central California; and $40 to $45/acre-ft in the Ogallala ground water region of the High Plains.

Howitt, et al. (12), reported similar results using a much different technique. Their interregional supply-demand model for California yielded prices at the margin of $23 to $35/acre-ft in the Central Valley and southern California and $7 in the Imperial Valley. Gollehon, et al. (10), show estimated prices for irrigation water in 11 Rocky Mountain subregions. This study is somewhat atypical since it studies the value of water that might be lost to the region or transferred to other uses. When the water supply is reduced by 20 percent, two regions showed water valued in excess of $20/acre-ft, four were between $10 and $20/acre-ft, and six were below $10/acre-ft.

The Department of Commerce recently sponsored a study of water value in the Ogallala region of the High Plains. The study showed a value of $60 to $80/acre-ft for water used in irrigation. These values move upwards with the passage of time, reflecting (assumed) increases in crop prices and yields through the year 2000.

The estimates of the value of water used to produce certain specialty crops (e.g., flowers, spices, berries) may be somewhat higher than the figures cited above. However, such uses will account for less than 10 percent of total irrigation water use in the foreseeable future. These crops are not, and probably will not be, of much significance for the formation of national water policy. This being the case, a rough estimate suggests that 90 percent of all irrigation demand is probably for water that costs no more than $40/acre-ft.

The Value of Water in Industry

Energy production is the major consumer of water used for industrial purposes in the arid West. Most of this water is used for cooling thermal-electric powerplants. Several processes can be used for cooling, depending on water scarcity and price.

Young and Gray (23) use an alternative cost approach to show that it is economical to convert existing plants from a pass-through cooling system to an evaporative cooling tower when water costs rise above $5/acre-ft (1982 price levels). Methods designed to conserve cooling water are much more expensive. Gold, et al. (9), in a study for the U.S. Environmental Protection Agency, report that the break-even points for combination wet-dry cooling systems run around $600/acre-ft, while the shift to a completely dry, water-free cooling system would be economical only if water were extremely expensive—perhaps as much as $1,400/acre-ft. Abbey's (1) comprehensive analysis of water and energy problems in the Colorado River Basin provides similar estimates. Hence, the large-scale stem plants proposed for several areas in the West could, if necessary, be willing to pay an amount many times the value of water in neighboring and competing agricultural uses.

Recent experience suggests, however, that even the large water requirements of huge powerplants can be met with relatively little loss of water to agriculture in the surrounding area. Much of the 45,000 acre-ft required by the Intermountain Power Project (IPP) in Utah will be met by using conveyance losses or water used on saline soils that have little or no present agricultural value.

Leigh (14) has studied the value of water for coal slurry pipelines. His values are based on cost savings that accrue from not having to rely on rail transportation to move the coal (the alternative cost method of measurement). The value of water in a Colorado-to-Texas pipeline system is estimated to exceed $1,600/acre-ft. This estimate of value is, however, extremely sensitive to changes in the level of railroad freight rates. Reductions in freight rates could reduce the imputed value of water, although it is not likely to drive the value below willingness to pay for irrigation water. That is, agriculture cannot expect to compete with this use of water.

The need for water in recovery of hydrocarbons from oil shale has received considerable attention. Valuing water in this use could be accomplished using the alternative cost method or by estimating the change in net income accruing to oil-producing firms. The alternative cost approach suggests that water could substitute for considerable capital and labor in the refining process and hence be very valuable. The change in net income approach requires that the production process be profitable before positive residual income can be imputed to water. Under current and anticipated petroleum prices, shale oil extraction is not economically feasible, therefore, water has a zero or negative value in this use.

Value of Water in Households

While willingness to pay for water delivered to households is readily observed and has been studied by many analysts, deriving a marginal value of water to households that is comparable and commensurate with estimates of raw water values in streams is, however, quite difficult. Household water that is treated (filtered and chlorinated), stored, and delivered to the user on demand is a much different economic commodity than the raw and untreated river water that is used in irrigation or industry. Hence, a deduction for treatment, storage, and delivery costs must be made to make the prices and values comparable. An estimate may be derived using a method suggested by Young and Gray (23) and based on data developed by Howe and Lineaweaver (12). This approach finds that lawn sprinkling is valued at about $150/acre-ft and inhouse uses at $250/acre-ft (in 1982 dollars). A weighted average of water in the two uses would be about $220/acre-ft. In another study Howitt, et al. (13), do not distinguish between industrial and household demand. Their municipal and household sector estimates for 1980 (in 1982 prices) are about $160 to $200/acre-ft.

An alternative estimate can be derived from market values of water in the Colorado-Big Thompson project (in northeastern Colorado) that can be transferred to urban uses. Gardner and Miller (8) report that the price of water rights—i.e., the price of exclusive rights to water—averaged $2,450/acre-ft in 1981. Converting this figure to an annual acre-foot value requires assumptions regarding the capitalization rate and expectations about future inflation. However, if the interest rate is about 8 to 9 percent (which seems plausible), and the planning horizon is long, the value of water is nearly equivalent to the $240 determined by Young and Gray (23) and Howitt, et al. (13).

Hydroelectric Power Generation

Because evaluation of hydroelectric projects has usually proceeded on the assumption that falling water is a free good, recorded efforts to value water in this use are rare. In recent years competition for water—even falling water—has intensified, so evaluation methods have had to be developed. The procedure that has emerged centers on the cost of generating electricity using some alternative method of generation (alternative cost method). When this method is used, the value of water is derived by deducting capital and operating costs of the generation and transmission system from the revenue earned by selling the power. The residual, if any, is attributed to the water resource (change in net income method). Specific value estimates vary, depending on the differences in head (the distance the water falls before turning the turbines), distances to load centers, costs of the steam-generating alternative, and the construction costs of the dam and storage facilities behind it. Even given these variables, values are also expressed for one site only or for several sites on a given reach of a river. Young and Gray (23) report single-site values ranging from $3.30 to $10/acre-ft in 1982 prices in the Western States. The higher values are associated with sites that have relatively high heads and can, thus turn larger turbines. Most of these sites are found on the Colorado River. Whittlesey and Gibbs (22) report values for power generation in the Columbia Basin of over $30/acre-ft (1982 prices) for water that goes through all of the dams below Franklin Roosevelt Reservoir, including Grand Coulee. This figure is higher than that reported by Young and Gray because of continued reuse at several generating stations and because of the higher costs associated with alternative energy sources in or near the Columbia River Basin. While single-site values for hydropower are not large relative to the values found in diversionary uses, diversions that are made high in a basin can lead to loss of large cumulative benefits stemming from reuse as the water passes through a number of facilities.

Valuing Water in Water Load Dilution

Water released for dilution of pollutants has value to the extent it reduces damage that the pollutants may impose on subsequent users. Precise estimates are difficult to derive since the detrimental effects depend on the particular pollutant, distance downstream, water temperature, rate of flow, and the quality of the waste-receiving water used for dilution. Most analysts have estimated values by assuming that the value of a unit of "clean" water is equivalent to the cost of treating effluent so that it does not reduce the quality of the water.

The results of these studies generally imply that dilution values are generally quite low. Merritt and Mar (16) showed dilution water in the Willamette Basin (Oregon) to have a value of about $1.30/acre-ft (1982 price levels). Gray and Young (11) applied the aforementioned technique to several regions in the West. Their estimates of value in dilution ranged from $0.08/acre-ft (Colorado Basin) to $3.25/acre-ft in the lower Missouri. Employing data from the Colorado River Board of California, Young and Gray (23), however, derived a value of water for dilution or reduction of salinity in the Colorado Basin at about $15/acre-ft.

The Value of Water in Water-Based Recreation

Water-based recreational services, by tradition and policy, are not often priced by market processes. Indeed, recreation and recreation services are so varied and so abstract that many people scoff at the notion that any reasonable value can be attributed to the resources used to produce them. The normal problems of valuing water are compounded since the value of water for recreation must be derived from a prior, synthetic, and sometimes arbitrary imputation of the value of the recreational services themselves. The problem is further complicated because the recreational uses of water are often complementary to other water uses rather than competitive with them. Water stored for irrigation, hydropower production, or flood control can be enjoyed by swimmers or fishing enthusiasts without diminishing its usefulness in its other uses. In such cases, it is difficult to value the water and only slightly less difficult to ascertain the value of the recreational experience.

However, the growing demand for recreation is creating situations in which recreational uses are beginning to compete with other classes of instream or offstream use. At this time, few analysts are working on measuring water values that are suitable for comparing allocations among alternative uses that include recreation.

Daubert, Young, and Gray (5) formulated a direct interview procedure to elicit hypothetical bids from recreationists on the value of water in flowing streams. Applied to a sample of visitors to the Poudre Canyon in northeastern Colorado, this approach yielded estimates of economic value related to river flow used for fishing, whitewater kayaking, and noncontact streamside recreation such as picnicking. The resulting marginal bid values for typical summer streamflow were converted to dollars per acre-foot and were $9/acre-ft for fishing, $5/acre-ft for whitewater sports, and $7/acre-ft for the noncontact recreational experiences. Walsh, et al. (21), performed similar analysis on western Colorado streams, reporting $13/acre-ft for fishing, $4/acre-ft for kayaking, and $2/acre-ft for rafting when flows were maintained at 35 percent of maximum.

These findings lend support to the notion that nonconsumptive uses, even though they are nonmarketed, have economic value to users. While many are skeptical of the validity of benefit estimates based on responses to questions regarding hypothetical situations, a preferable alternative technique to generate quantitative estimates of instream flow values has not been developed. While recognizing that estimates using this technique are subject to more than the usual error, they appear to be reasonable reflections of user preferences. Since these estimates are for values in a public, nonexclusive use, they must be used with great care, especially when incorporated into water-management policy decisions.

Fish and Wildlife Habitat

Efforts to value habitat directly in economic terms are relatively recent. Many suffer from one or more of the potential difficulties noted earlier, particularly in valuing total product rather than incremental units of water.*

The problem remains of relating physical water requirements to habitat productivity, an issue that appears not to have been addressed in literature that is readily accessible. The estimates made by Lynn, et al. (15), indicate a marshland value of less than $1/acre. Water supplies per acre for the habitat of one crab species would not be highly valued in strict economic terms.

Navigation

Provisions of facilities for inland waterways navigation has always been an important part of Federal water policy. Estimates of the value of water for this purpose are almost nonexistent, since the usual approach to benefit-cost analysis of navigation projects implicitly assumes water to be a free good (as with hydropower). A sample approach (23) credited water with the savings from transporting commodities by water rather than by rail, pipeline, or truck. They reported positive values for water used for navigation only on the Mississippi, Ohio, and Tennessee River systems. Elsewhere, such as on the Missouri and the Columbia Rivers, the total cost of building and maintaining a navigation system exceeded the savings: no benefit was creditable to navigation.

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*See Lynn (15) for an analysis of the conceptual issues, and some empirical estimates relating to blue crab production on the Florida gulf coast.

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Appendix D

Method of the Study

Most OTA studies rely on outside experts to guide the study, suggest topics for special emphasis, provide specially tailored research summaries, and review staff work. Separate but sometimes overlapping groups filled each of these roles in this assessment (table D-1). An advisory panel provided overall guidance throughout the course of the assessment. A number of planning workshops and working group meetings were held to address more specific topics and several reviewers examined the draft assessment. Other OTA studies have used similar groups but the number of people involved in this assessment was larger than average.

This assessment also was unusual in its strong regional focus. Staff from OTA made extensive site visits throughout the West, many meetings were held in the region, and outside experts were almost exclusively drawn from Western States.

Phase 1: Planning

Preliminary meetings were held while OTA staff visited private sector, academic and government experts in 12 of the 17 Western States. Three planning workshops, in Denver, Salt Lake City, and Berkeley, provided additional background information and identified important issues. Many of the colleagues who took part in these initial sessions participated throughout the 2-year assessment.

The advisory panel had its first meeting 2 months after the assessment began. Its 19 members included farmers, ranchers, scientists, government officials and representatives from private industry and public interest groups. Dr. James Kendrick, Jr., Vice President for Agriculture and University Services, University of California-Berkeley, chaired the panel. Members discussed the general format and scope of the study and advised that OTA form several working groups to analyze issues in more detail.

Four working groups (one each on rangeland, irrigation, dryland agriculture, and social sciences) were formed and met 1 month later. Each group identified several topics for contractors' reports, completed detailed outlines of each topic, and suggested several potential authors.

Phase 2: Commissioning and Evaluating Contractors' Reports

Working group and advisory panel members helped to recruit contractors and, in some cases, also served as authors. Fifteen major papers were

Table D-1.—Assessment Meetings

Group	Date	Location	Members attending
Advisory Panel:			
Meeting 1	Oct. 22-23, 1981	Washington, D.C.	18
Meeting 2	May 26-27, 1982	Washington, D.C.	18
Meeting 3	Oct. 28-29, 1982	Washington, D.C.	18
Meeting 4	Mar. 29-30, 1983	Washington, D.C.	18
Planning Workshops:			
Drylands	Sept. 11, 1981	Denver, Colo.	11
Rangelands	Sept. 18, 1981	Salt Lake City, Utah	10
Irrigation	Sept. 25, 1981	Berkeley, Calif.	11
Workgroups:			
Meeting 1:			
Rangelands	Nov. 19-20, 1981	Washington, D.C.	7
Drylands	Nov. 12-13, 1981	Washington, D.C.	7
Irrigation	Nov. 23-24, 1981	Washington, D.C.	8
Social Science	Dec. 7-8, 1981	Denver, Colo.	11
Meeting 2:			
Rangelands	Apr. 26, 1982	Denver, Colo.	7
Drylands	Apr. 27, 1982	Denver, Colo.	7
Irrigation	Apr. 29, 1982	Denver, Colo.	8
Social Science	Apr. 28, 1982	Denver, Colo.	11

SOURCE: Office of Technology Assessment.

commissioned and six smaller ones were contributed without contractual arrangements. The authors met with corresponding working group members during the second meeting. Draft papers were reviewed and suggestions made for final versions. The second meeting of the advisory panel evaluated the results of the working group reviews and provided additional comments for the authors. Final copies of the contractor's reports were completed at the midpoint of the assessment and served as important source materials.

Phase 3: Preparing the OTA Assessment

The meetings of the authors, working groups, and advisory panel provided OTA with clear indications of strengths and weaknesses of the assessment's draft organization and background information. As a result, the assessment was reorganized to follow the hydrologic cycle instead of agricultural land uses. In some cases, it was necessary to research and synthesize additional information from the scientific literature or to bring in specialists to fill significant gaps. Extensive staff work was done during preparation of the first assessment draft to complete these tasks.

The advisory panel reviewed the first draft of OTA's work during its third meeting, reaffirmed the desirability of the hydrologic cycle format, and suggested modifications. These changes were made before the draft was sent to about 50 independent reviewers from a wide range of organizations. The external review process was finished by the time of the fourth and final advisory panel meeting 2 months before the assessment was due for delivery to the OTA Congressional Board. Discussions at the final meeting focused on the major findings of the assessment and policy options for Congress.

The results of this assessment are presented in two documents. This volume contains the full assessment of domestic issues. A smaller background paper, "Water Related Technologies for Sustainable Agriculture in Arid/Semiarid Lands: Selected Foreign Experience," was also prepared. It presents six case studies of innovative foreign practices that may have important wider applications for sustainable agriculture in arid/semiarid lands.

Appendix E

Acronyms and Glossary

Acronyms

AGNET —Agricultural Computer Network
BOD —biochemical oxygen demand
CAM —crassulacean acid metabolism
CAP —Central Arizona Project
CBO —Congressional Budget Office
CROHMS —Columbia River Operation Hydromet Management System
DBCP —dibromochloropropane
DOC —Department of Commerce
DOD —Department of Defense
DOI —Department of the Interior
EDIS —Environmental Data and Information Service
EPA —Environmental Protection Agency
FIARBC —Federal Inter-Agency River Basin Committee
FIFRA —Federal Insecticide, Fungicide, and Rodenticide Act
FWPCA —Federal Water Pollution Control Act
GAO —General Accounting Office
HM —Hydrometeorological Streamflow Prediction
ISS —irrigation scheduling services
MCL —maximum contaminant level
NAS —National Academy of Sciences
NASQAN —National Stream Quality Accounting Network
NAWDEX —National Water Data Exchange
NCAR —National Center for Atmospheric Research
NCSL —National Conference of State Legislatures
NNRIS —Nebraska Natural Resources Information System
NWS —National Weather Service
OTA —Office of Technology Assessment
OWRT —Office of Water Research and Technology
PIK —payment-in-kind
RCRA —Resource Conservation and Recovery Act
R&D —research and development
SAR —Sodium Absorption Ratio
SCS —Soil Conservation Service
SSARR —Streamflow Synthesis and Reservoir Regulation
TNRIS —Texas Natural Resources Information System
USDA —U.S. Department of Agriculture
USGS —U.S. Geological Survey
WATSTORE—Water Data Storage and Retrieval System
WHO —World Health Organization, United Nations
WRC —Water Resources Council
WRSIC —Water Resources Scientific Information Center
WUE —water-use efficiency

Glossary

Acre-foot: A measure of the volume (e.g., irrigation water) that would cover 1 acre of land (43,560 square feet) to a depth of 1 ft. In the metric system, volume is expressed as cubic meters. One acre-ft equals 1,233.6 cubic meters.

Agriculture: The human use of land for direct production of plants and animals and materials produced by them. For purposes of this assessment, agriculture does not include the use of land primarily for the production of timber.

Agronomic water-use efficiency: The amount of harvestable or economic biomass produced per water lost by transpiration and evaporation.

Arid and semiarid lands: Those lands where crop-water requirements exceed the plant-available water (growing season precipitation plus soil water stored in the root zone) by a significant amount. Arid and semiarid lands comprise about one-third of the contiguous United States, principally the 17 Western States—the focus of this study.

Biological water-use efficiency: The total dry weight of plant material produced per total water lost by transpiration.

Dryland agriculture or farming: Crop production without irrigation in regions where available water is the most limiting factor.

Efficiency: The amount of output per unit of input. Efficiency can be measured at many different scales and for many different factors. For example, "irrigation efficiency" may refer to several different measures of theoretical, technical, economic, and actual water use, within irrigation districts, on farms, or in fields.

Evaporation: The process by which a liquid is changed into a gas. Evaporation that takes place from the seas and oceans is the main source of water on land areas.

Evapotranspiration: The loss of water from the soil by evaporation and from plants by transpiration.

Externalities: Unintended consequences of an exchange or a production process.

Ground water: The part of the subsurface water below the soil water zone in spaces, or interstices, of subsurface geological formations or of rock or unconsolidated sediment completely saturated with water.

Ground water "mining": Withdrawal of ground water at a rate in excess of its natural or artificial recharge.

Hydrologic cycle: The central concept in hydrology that relates the interdependence and continuous movement of all forms of water through the vapor, liquid, and solid phases. The components of the hydrologic cycle are: precipitation, evaporation, transpiration, infiltration, percolation, runoff.

Infiltration: The process whereby water soaks into, or is absorbed by the soil layers.

Irrigation agriculture or farming: Crop production using the application of water to lands primarily to provide the water for plant growth that is not provided by rainfall during the growing season.

Long-term: Means more than one human lifespan (approximately 70 years) from the date of this report.

Onfarm irrigation efficiency: The ratio or percentage of the volume of water stored in the soil root zone and used by the crop to the volume of water delivered to the farm.

Percolation: The downward flow of water through soil and permeable rock formation to the ground water table.

Precipitation: Water added to the surface of the Earth from the atmosphere. It may be either liquid (e.g., rain and dew) or solid (e.g., snow, frost, and hail).

Rangeland: Those areas on which the native vegetation is predominantly grasses, grasslike plants, forbs, and shrubs. These lands have generally been thought unsuitable for cultivation and have traditionally been used for grazing domestic livestock. More recently, rangelands have been managed also for the production of wood and other plant products, water, recreational purposes, and wildlife habitat.

Renewable natural resource base: Includes soil, water, and all the physical, chemical, and biological components of agricultural resource systems.

Runoff: The portion of precipitation that comprises the gravity movement of water in surface channels or depressions.

Soil water (or soil moisture): The part of the subsurface water immediately below the surface in the spaces, or interstices, of the soil.

Subsidence: Collapse of underground, water-bearing formations caused by ground water overdraft.

Subsurface water: All water that exists below the surface of the Earth in interconnected openings ("interstices") of soil or rock, includes soil water and ground water.

Total streamflow: Computed flow that includes effects of consumption, water transfers, and evaporation from manmade reservoirs, but not ground water overdraft.

Transpiration: The process by which water vapor passes through a living plant and enters the atmosphere.

Water: A mineral composed of two parts hydrogen to one part oxygen with a unique combination of properties: liquid at room temperature, requires large amounts of energy for conversion from liquid to vapor and from solid to liquid, resistant to temperature changes, strong attraction between its own and other molecules, dissolves many substances, transmits visible light but absorbs thermal radiation.

Water, "new": Additional water available at a site in excess of that which would be available as a result of unmodified natural processes. This would include that made available, for example, from interbasin or intrabasin transfers, weather modification, or watershed management. This concept has little meaning from a hydrologic point of view. The total volume of water within a definable region is fixed by the hydrologic cycle. Water can be transferred only from one phase or location to another, while the term "new" water suggests that it is created. Additions at one point will inevitably produce deficits at another because of fundamental water-balance constraints. There are no exceptions to this although the lack of knowledge about some processes makes it appear that "new" supplies are available.

Water pollution, nonpoint sources: Diffused wastes reaching water through land runoff, washout from the atmosphere or other means. These pollutants are extremely difficult to control.

Water pollution, point sources: Waste discharges from identifiable points. These pollutants are amenable to direct control.

Water "savings": The amount of water that remains for additional use after technological manipulation of the hydrologic cycle. Technologies include evapotranspiration suppression, reduced agricultural withdrawals, and decreased infiltration and deep percolation. A water "savings" can only be defined in the context of the water balance of a particular site and is largely an economic, not a hydrologic, concept. Hydrologically, water cannot be "saved" or "lost." It can only be transferred from one place or phase of the hydrologic cycle to another.

Water supply: The streamflow volume that would occur at the outflow point of each subregion if consumption were eliminated, ground water overdrafting were discontinued, and current water transfer and reservoir practices were continued.

Water table: The upper surface of the zone of ground water.

Water use, Consumptive: Water withdrawal and use in such a way that it is no longer available for additional uses—e.g., due to evaporation, transpiration, and ingestion by animals.

Water use, Nonconsumptive: Withdrawals and use that return water to supplies for additional use—e.g., irrigation "return flows," hydroelectric energy generation, and instream-flow requirements.

Watershed: The fundamental geographic units of hydrology, land area surrounded at its perimeter by highlands that cause precipitation falling within the watershed's bounds to flow or drain generally toward its center to form rivers or streams; a watershed is also known as a river basin, and could be as large as that of the Missouri River Basin (at least 500,000 mi²) or as small as an ephemeral tributary to that river (a few tens of acres).

Conversion Table for Common Measures

Area

1 hectare equals: 100 meters × 100 meters or 10,000 square meters; 2.471 acres; or 0.00386 square miles

1 acre equals: 0.405 hectares

Volume

1 cubic meter equals: 35.31 cubic ft; or 264.2 U.S. gal

1,000,000 cubic meters equal: 810.6 acre-ft

1 acre-ft equals: 1,233.6 cubic meters; or 325,931 gal

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Appendix F

Contractors, Work Groups, and Workshops

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